Rapid Photometry of Supernova 1987A: A 2.14 ms Pulsar? [1]

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Abstract

We have monitored Supernova 1987A in optical/near-infrared bands using various high-speed photometers from a few weeks following its birth until early 1996 in order to search for a pulsar remnant. While we have found no clear evidence of any pulsar of constant intensity and stable timing, we have found emission with a complex period modulation near the frequency of 467.5 Hz – a 2.14 ms pulsar candidate. We first detected this signal in data taken on the remnant at the Las Campanas Observatory (LCO) 2.5-m Dupont telescope during 14-16 Feb. 1992 UT. We detected further signals near the 2.14 ms period on numerous occasions over the next four years in data taken with a variety of telescopes, data systems and detectors, at a number of ground- and space-based observatories. In particular, an effort during mid-1993 to monitor this signal with the U. of Tasmania 1-m telescope, when SN1987A was inaccessible to nearly all other observing sites due to high air-mass, clearly detected the 2.14 ms signal in the first three nights' observations. The sequence of detections of this signal from Feb. '92 through August '93, prior to its apparent subsequent fading, is highly improbable ($< 10^{-10}$ for any noise source). In addition, the frequency of the signals followed a consistent and predictable spindown ($\sim$2-3$\times 10^{-10}$ Hz/s) over the several year timespan ('92 - '96). We also find evidence in data, again taken by more than one telescope and recording system, for modulation of the 2.14 ms period with a $\sim$1,000 s period which complicates its detection. The 1,000 s modulation was clearly detected in the first two observations with the U. Tas. 1-m during mid-1993. The characteristics of the 2.14 ms signature and its $\sim$1,000 s modulation are consistent with precession and spindown via gravitational radiation of a neutron star with an effective non-axisymmetric oblateness of $\sim 10^{-6}$. The implied luminosity of the gravitational radiation exceeds the spindown luminosity of the Crab Nebula pulsar by an order of magnitude. Due to the nature of the 2.14 ms signature and its modulation, and the analysis techniques necessary for detection, it is difficult to determine the overall probability that all aspects of the signal are real, though it has remained consistent with an astrophysical origin throughout the several year timespan of our study.

Key words: Stars: neutron, Stars: pulsars: general, Stars: pulsars: individual (PSR1987A), Stars: supernovae: individual (SN1987A),

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1 Introduction

Since the detection of a neutrino burst of $\sim$10 s duration on Feb. 23, 1987 (Bionta et al. 1987, Hirata et al. 1987), there has been very little direct evidence of the nature of the compact remnant of Supernova 1987A (SN1987A) in the Large Magellanic Cloud (LMC). The neutrino flux of $\sim 2.5 \times 10^{53}$ergs, ranging in energy from 6 to 39 MeV, detected a few hours prior to the initial

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rise in the optical flux, corresponds to 100 MeV for each of 1.6×10^{57} nucleons, consistent with the binding energy of a neutron star of one to two solar masses (Schaeffer et al. 1987, Burrows 1988, Arnett et al. 1989). Limits on the neutrino emission from SN1987A for longer time intervals following the first outburst can not, by themselves, eliminate the possibility of the subsequent formation of a black hole from material accreted later. However, a neutron star surrounded by atoms with high atomic weights will have an Eddington limit near 10^{35} ergs/s due to the large photon absorption cross sections involved (Fryer et al. 1999). Thus, the subsequent creation of a black hole by infall onto the neutron star born in SN1987A (Brown et al. 1992), must be considered unlikely.

There has also been little evidence of the energy output of a young pulsar embedded within SN1987A. As of day 1500, the luminosity of SN1987A in the ultraviolet, optical and infrared was less than 8×10^{36} ergs/s (Suntzeff et al. 1992). By day 3600, the luminosity had fallen to between 1.25 and 2×10^{36} ergs/s (Suntzeff et al. 1999). By now, however, the amount of radioactivity which powers the remnant luminosity is highly uncertain. In addition, "freeze-out" in the diffuse remnant, wherein its ions have lost the ability to keep up with the luminosity through recombination due to their low density, has long since set in (Fransson & Kozma 1999). Because of these considerations, no very stringent upper or lower limits can be placed on the luminosity of any compact remnant. Thus a neutron star accreting high Z material at its Eddington limit could still easily escape detection in such a flux. Young, moderately rapidly spinning and strongly magnetized pulsars, such as the Crab and PSR0540-693, with electromagnetic luminosities up to several times 10^{38} ergs/s and much greater than the highest estimates of the remaining radioactive luminosity, would be much more difficult to hide. Such pulsars could completely ionize the gas contained in the entire diffuse remnant within 10-20 years, and then power the SN1987A optical remnant via synchrotron or bremsstrahlung processes to near 12th and 13th magnitudes, respectively, far in excess of the $\sim$18.5 magnitudes now observed.

A slowly rotating pulsar, however, would not be excluded by the diffuse remnant luminosities quoted above. Even though rapidly-spinning pulsars would be difficult to detect in the radio band due to the high dispersion measures implied, slowly rotating pulsars would not, as long as the plasma frequency/free electron density close to the pulsar is lower than several hundred MHz/2×10^{9} cm^{-3}. No such slowly rotating pulsar has yet been detected, nor have any ever been associated with young remnants (see, e.g., Lorimer et al. 1998), consistent with the lack of any statistical need to inject them as such into the general pulsar population (Lorimer et al. 1993, however, Foster et al. 1990). Of course the possibility of a slowly rotating pulsar with a *weak* magnetic field can not be excluded on the basis of luminosity alone. However, the evidence for a non spherical explosion of SN1987A is now strong (Papaliolios et al. 1989, Pun &

Kirshner 1999), and in §4.3 we argue that this and the remaining details particular to SN1987A make the formation of a slowly-rotating, weakly-magnetized neutron star unlikely.

On the other hand, a rapidly-rotating, weakly magnetized neutron star, i.e., a "millisecond" pulsar, could easily hide within the diffuse remnant for many decades, unless it produces a substantial amount of pulsed radiation in a less-dispersed, higher frequency, more easily-detected band, such as the optical. Even should this be the case, timing instabilities such as "glitching" (Boynton et al. 1969, Nelson et al. 1970, Anderson & Itoh 1975, Ruderman 1976, McCulloch et al. 1990, Flanagan 1990), precession/nutation (Nelson et al. 1990, Pines & Shaham 1972a,b) and/or r-mode instabilities (Lindblom et al. 1998, Owen et al. 1998) could reduce the detectability of any such pulsar, particularly if it is spinning rapidly. Even though none of these instabilities have ever been seen in any known ms pulsar, their possibility can not be excluded in the compact SN1987A remnant, because it is still so young ($\sim$12 years old). By contrast, the youngest known millisecond pulsar, 1821-24 in the globular cluster, M28 (Lyne et al. 1987), has an age of 30 million years. Finally, vortex pinning, once thought to limit the triaxiality affecting the rotation of such a young ms pulsar (Shaham 1977,1986), appears unlikely to be a factor since the recent discovery of the 16 ms pulsar, J0537-6910, in N157B (Marshall et al. 1998a,b, Gotthelf & Wang 1998), which was probably born spinning with a 7 ms period.

Opacities from a surrounding accretion disk might also reduce the visibility of any pulsar remnant, no matter how slow its spin. To make matters worse, quantitative estimates of the visibility of such a pulsar within the remnant are scarce or unpublished (Pinto 1999), so it is hard to know in advance just how detectable any pulsar remnant should be. Worse still, any opacity would not necessarily decrease monotonically with time due to pulsar motion through the remnant, clumping, growth of dust grains, etc.

The progenitor star, Sk - 69°202, was associated with a region of very active star formation overlying a much older field population (Sanduleak 1969, West et al. 1987, Panagia et al. 1999). Aside from the young, Crab-like pulsars, PSR0540-69 (Seward et al. 1984, Middleditch & Pennypacker 1985), and J0537-6910, only three "normal" (and no ms) pulsars are known in the LMC, and only one (non-ms) pulsar is known in the SMC (McConnell et al. 1991, Kaspi et al. 1994). Extensive searches for radio ms pulsars in the LMC have yet to be made.

Prior to this work, repeated observational attempts (Pennypacker et al. 1989, Ögelmann et al. 1990, Kristian et al. 1991, Percival et al. 1995, Manchester & Peterson 1996) have failed to detect any "normal" pulsar in the radio or optical bands – a disappointment to theorists who saw most of their early expectations confirmed (Chevalier 1992a,b). Thus, barring persistently large opacity over the last decade, there is substantial evidence for a lack of any "normal" pulsar in SN1987A with stable spin-down parameters and constant pulse profile (see also Appendix A). However, given the extreme youth of SN1987A, there are no a priori reasons to expect persistently low opacity from the diffuse remnant, or normality from the compact one (see §§4.1.1-4.1.2). There is, in fact, substantial evidence, which is discussed at length in the remainder of this work, that a pulsar with a spin period of 2.14 ms does indeed lie within SN1987A.

1.1 Overview

This paper presents evidence of an unusual 2.14 ms optical signal from SN1987A and estimates the probability that it is real and astrophysical to be $\sim 10^{-10}$ as of August '93, from data taken *subsequent* to its discovery during Feb. '92. This probability remains low in spite of the fading of the signal after August '93. We also place the strictest upper limits to date on the presence of any "normal" pulsar within the SN1987A remnant.

This work briefly discusses, in §2, the basic observational method, gives a historical account of the results, including the discovery of sideband modulation of the 2.14 ms signal, and finishes with a summary of all of the results. Section 3 gives a detailed discussion of the sideband modulation first discovered in the Feb. 6, '93 data, and finishes its treatment of the data issues with a section discussing the reality of the 2.14 ms signal, the decrease of the 1,000 s modulation period and the spindown of the 2.14 ms signal.

Section 4.1 discusses the timing behavior of the 2.14 ms signal and its $\sim$1,000 s modulation. The case for pulsar precession and/or r-mode instabilities is formally presented here in §4.1.1. A short discussion of pulsar emission mechanism in §4.2 is followed in §4.3 by the implications of the 2.14 ms signal and what we may have learned from SN1987A about pulsar formation. Finally, we discuss the future prospects for the study in §4.4, and conclude in §5.

Appendix A presents evidence for the lack of visibility of any "normal" pulsar in SN1987A, which includes a brief discussion of the nature of pulsar spindown and a much more detailed discussion of the deep pulsar search done on the data from the Cerro Tololo Inter-American Observatory (CTIO) 4-m during Dec. '93. This search yielded upper limits at 24^{th} magnitude (in the 500 - 900 nm band) for any pulsar with constant pulse profile and sufficient rotational stability to phase over a few days. Appendix B, §B.1 completes the discussion of the Nov. '92 data, while §B.2 presents the data from Tasmania and the High Speed Photometer (HSP) of the Hubble Space Telescope (HST). Recent results, and further means of recognizing them, are discussed in §B.3. Appendix

C discusses the data acquisition and lists the large tables of observations and results.

2 Initial Observations & Results

2.1 Basic Observational Method

Optical/near-infrared observations of SN1987A were made starting a few weeks after onset of SN1987A through February of 1996. Typically in these observations, the numbers of detected photons from SN1987A viewed through a small aperture during consecutive 20-200 μs time windows were recorded on tape.

The data were subsequently downsummed to 200 μs time windows and then Fourier transformed. The resulting Fourier spectra were examined over the $\sim$0.02 - 2,500 Hz frequency region, since this bandwidth encompasses the rotation frequencies and first few higher harmonics of all known pulsars. The time integration of photon counts in such 200 μs windows is equivalent to a Nyquist filtering of the data for which the sensitivity in the Fourier spectrum drops by a factor of $2/\pi$ at 2,500 Hz. The resulting Fourier spectra were examined over this bandwidth for significant single peaks of power and for significant trains of harmonic power at half- and integral harmonic frequencies of the single peaks (Middleditch et al. 1992). The text in Appendix C gives further observational details.

2.2 Historical Account of Results

2.2.1 Brief Summary

The observations of SN1987A considered in this work span the interval 1992-1996. Those made from the Chilean observatories are listed in Table C.1, and those made from other observatories are listed in Table C.2 (both tables in Appendix C). We have reported earlier (Pennypacker et al. 1989, Kristian et al. 1991) on the negative results from other observations through February of 1990. The two observations made since that time and prior to Feb. '92 fall outside the scope of this work, because they are less sensitive due to the greater remnant brightness, larger apertures used, and/or shorter observation times. In addition it is likely that the opacity of the SN1987A diffuse remnant was higher than it was for observations during and subsequent to Feb. '92. Thus these earlier observations have little bearing on either the investigation of the reality of the 2.14 ms signal, and/or the persistent lack of any other credible pulsar signal. In any case, analysis of these runs revealed no significant signals and nothing near 2.14 ms.

The 2.14 ms signal was first discovered at LCO during a three-night observing run in Feb. '92. The observations with the U. Tas. 1-m telescope, the first few results of which strongly support the reality of the 2.14 ms signal, commenced after the first year of "detections" at LCO and CTIO. Further details are given in Appendix C.

2.2.2 Initial Analysis Specifics

The data from the three nights at LCO (UT Feb. 14-16, 1992) were searched for signals as described above in §2.1, first by analyzing each night separately, and then by analyzing all three nights combined using billion-point Fourier transforms in a process similar to that described in Appendix A, §A.2. In this case, four trial "decelerations" were used in order to span a range of frequency derivatives from 0. to that of the Crab pulsar (-3.8×10^{-10} Hz/s) for a pulsar spinning with the same frequency ($\sim$30 Hz).

The detection is serendipitous in that the spacing of the $\frac{\partial f}{\partial t}$'s was far too sparse for a 2.14 ms signal. Had the $\frac{\partial f}{\partial t}$ observed not been close to 0 (or one of the other three trial $\frac{\partial f}{\partial t}$'s) the 2.14 ms signal would not have been detected. In analysis of the original 50,000 Hz data the signal persisted at exactly the same frequency and thus could not have been caused by aliasing from events at other, higher frequencies. Since data were not obtained continuously over the 50-hour time span, about a half dozen other, less significant (f,$\frac{\partial f}{\partial t}$) candidate pairs for this event exist (see Table 1, but note that the components given have all been shifted away from the "true" values by the subsequently discovered modulation). The probability of finding such an event anywhere in such a billion point FFT is $\sim$1%, consistent with no similar event occurring in a deeper f-$\frac{\partial f}{\partial t}$ search done on more sensitive data taken later, which utilized 22 separate billion point FFT's (see Appendix A).

For all of the data taken since this Feb. 92 "discovery" run, in addition to the general night-by-night search of all frequencies which was always made, a targeted search was made for high power nearest the extrapolated 2.14 ms fundamental frequency ($\sim$467.5 Hz) and the 2nd harmonic ($\sim$935 Hz). In addition, the complex Fourier amplitudes nearest both frequencies were summed in a particular phase relation designed to be sensitive to pulse profiles with sharp "upward" spikes (for details, see §2.3 and Eqn. 1). Other than the f-$\frac{\partial f}{\partial t}$ search done on the Dec. '93 data (Appendix A), no further general f-$\frac{\partial f}{\partial t}$ searches were made because, as will soon become clear, the frequency stability of the 2.14 ms signal, which was fortuitously good during the Feb. '92 observation, had deteriorated by Feb. '93 to the point which made such searches pointless.

Table 1
Pulsation Parameters from UT 14.0820-16.1609 1992

Frequency[a] (Hz)	Derivative[a] (Hz/s)	-ln(Probability)[b]
467.4933886(4)	$-4.11(20)\times10^{-11}$	27.45
467.4933831(4)	$-1.96(10)\times10^{-10}$	27.05
467.4933765(4)	$-4.84(24)\times10^{-11}$	24.85
467.4933823(4)	$9.84(60)\times10^{-11}$	23.3
467.4933902(5)	$-3.53(20)\times10^{-10}$	19.6
467.4933976(5)	$-2.03(13)\times10^{-10}$	19.5

[a]As determined by folding the data into 20 phase bins. Although greater statistical significance results from using only 11 bins, the systematic frequency and derivative shifts due to the centering of the cruder bins (as, e.g., in the highest bin of the main pulse) would be greater.
[b]As determined by folding the data into 11 phase bins, using the parameters derived from folding into 20 phase bins, (i.e., not re-optimized with 11 bins) and thus, a partially "blind" measure of probability.

Targeted "looks" at the Fourier power on the f-$\frac{\partial f}{\partial t}$ plane, near f=1./(2.14 ms) and the first two higher harmonics, were made in a few cases where the 2.14 ms signal appeared to persist over more than one night, but only to investigate the timing stability of the 2.14 ms signal.

The pulse profile of the 2.14 ms signal from Feb. '92 was checked by folding the data at the "best" $(f, \frac{\partial f}{\partial t})$ combination into 20 phase bins per cycle (Figure 1). The error bars plotted are derived only from the square root of the counts in each bin. However, the χ^2 expected for 5,000 Hz data rebinned into 20 bins per cycle of 467.5 Hz is only 7.79 due to the rebinning. The most sensitive test of statistical significance occurs when folding 5,000 Hz data into only 11 phase bins, which has an expected χ^2 of 6.23.[13] The associated probabilities of such pulse profiles, as verified by both mathematics and statistical trials, can be obtained by scaling the χ^2 by (dof = (5000/467.5 -1))/6.23=1.556, and logarithmically interpolating to account for the non-integral degrees of freedom (dof=9.695). Such an analysis shows that the event was about as unlikely as a single peak with 27.45 times mean noise power (i.e. Prob. $\sim e^{-27.45}$), or a somewhat rare event in a handful of FFT's of a billion points of *contiguous* data (as most of the data stream was padded with a constant rate to fill in

[13] As the data were cut and weighted according to their values and amount of overlap with the phase bins, and since 5000/467.5 $\leq$11, nothing is missed by the 11-bin profile which appears in the 20-bin profile, but the plot of the pulse profile with 11 bins, would, however, be less visually satisfying than one with 20 bins.

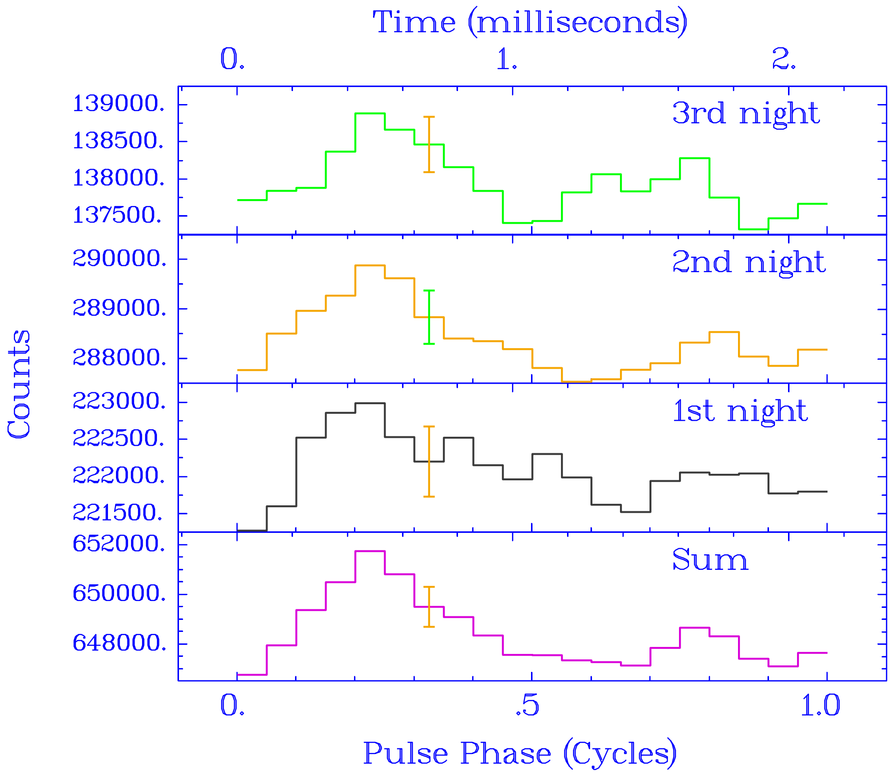

Fig. 1. The pulse profiles for the 2.14 ms periodicity detected on Feb. 14-16, '92 with the LCO 2.5-m telescope.

the non-observing intervals, there were only about 240 million points of data from the three nights in Feb. '92, thus about 120 million independent power points in each of these four, billion point FFT's).

The pulse profiles show the signal was weakest during the first night, and strongest during the "good" part of the third night (measured in terms of accumulated χ^2 per unit time). During the last, and "poor seeing" part of the third night,[14] when light from SN1987A was lost outside of the aperture and light from neighboring stars leaked into the aperture, the 2.14 ms signal was nearly undetectable – suggesting that the signal was indeed coming from SN1987A, as does also the greater strength of the 2.14 ms signal during the first part of the previous night (Feb. 15), when SN1987A was observed through a lower airmass, and consequently, better seeing conditions.

[14] The observing conditions for these three nights were superb, easily allowing the monitoring of SN1987A through a 3.77 arc second diameter circular aperture, except for the later hours of the last night (Feb. 16), which were marred by a sudden frontal passage.

We continued to observe SN1987A in the year following the initial appearance of the 2.14-ms signal. Aside from the general night-by-night search for significant single frequencies or trains of harmonics, a targeted search was made using the sum of the complex Fourier amplitudes near the ~467.5 Hz fundamental frequency, $a(f)$, with those near the ~935 Hz second harmonic, $a(2f)$ in the following way:

$$a_{sum} \ = \ (\ \|a(f)\| \ + \ e^{i(\phi(2f)-2\phi(f))}\|a(2f)\| \ )/\sqrt{2}, \tag{1}$$

where $\|a(f)\|$ is the complex modulus of $a(f)$, $\phi(f)$ is the phase of $a(f)$, and $\phi(2f)$ is the phase of $a(2f)$. If the Fourier spectra near f and $2f$ have been normalized so that the mean power is unity (as these always are), which guarantees that their statistics will be simply exponential in power ($Prob(P)dP = e^{-P}dP$, where P is power), then $\|a_{sum}\|^2$ will also have identical exponential statistics. For a_{sum} the phases in Eqn. 1 were set so that the Fourier amplitudes of any periodic "peak" (in time) deviating from the mean counting rate (of the values in the pulse profiles as, for example in Figure 1) in a positive way would add directly, or "in phase". Thus, when the Fourier powers of $a(f)$ and $a(2f)$ are roughly equal, the Fourier power of a_{sum} would be close to their sum.

At first, even with this tool, we found no clear signal in the November 1992 data. We discuss this first unsuccessful targeted search, and the signal ultimately found in this data, in Appendix B, §B.1.

On the night of 6 Feb. UT 1993, in a run on the LCO 2.5-m which lasted ~80 minutes before high humidity forced an early termination (conditions were otherwise perfect), an unusual pattern of power appeared in the sum of the Fourier spectra from frequency regions encompassing the extrapolation of the Feb. 92 frequency near 467.4843 Hz and twice this value. The resulting individual and sum power spectra are shown in Figure 2.

The three high peaks in the sum power spectrum are, to within errors, evenly spaced by 0.00214 Hz, modulo the 467.5 Hz fundamental frequency, and immediately suggest a periodic modulation in the phase/frequency and/or amplitude of the 2.14 ms signal with a period of ~467 *seconds.* The 467.48429 Hz frequency of the central peak (1/3 of the frequency of the top scale) also indicates a *mean* spindown for the pulsar, implied by the 2.14 ms signal for the ~1 year interval between Feb. 92 and Feb. 93, of about -3×10^{-10} Hz/s, consistent with the most extreme (but, statistically, one of the least favored) of the half dozen $\frac{\partial f}{\partial t}$ values for the Feb. 92 data (the extrapolation using the "best" derivative, -4.11×10^{-11} Hz/s, predicts a frequency of 467.4921 Hz – see

Table 1). Further analysis would resolve this discrepancy (see §3.3.2).

The probability of finding three such peaks in the sum spectrum, each exceeding 10 times noise power, is low (not*one* such peak appeared in the sections of spectra shown in the three lower frames of Fig. 2, and, arguably, there is quite a bit of signal in the two lowest frames, at least, to which noise could have added – see further details in §3.1). Of course similar graphs, such as Fig. 7, were made from the five other nights in the Feb. '93 LCO and CTIO observing runs. Each of these has about 400 independent points in its respective sum spectrum, which increases by a factor of 3 when the Fourier spectrum is finely interpolated[15] as it always is in this work. So $1200 \times e^{-10} = 0.05$ which is small and consistent with our observations, but not so small when five more frames are considered.

Now, however, there is a second peak within 0.15 of the whole frequency range, in which the power exceeds 10 again. The degrees of freedom involved include 0.15×2 (directions) $\times 400$ bins$\times 3$ (fineness factor) = 369. When another e^{-10} factor is included, the probability is further multiplied by a factor of 0.01688 and falls to 0.005. When a third peak with power exceeding 10 appears *exactly* between the first two peaks (again throwing in a factor of 3 for fineness), the probability falls to below 10^{-6}. The results would not have changed much if we had allowed the middle peak to appear 2nd and then allotted 2 or 3 different locations for where the third peak could fall. Even factoring in the longer run lengths for the other five observations (the 2.14 ms signal would have been out of range toward lower frequencies in these runs), and the results from Nov. '92, all with *no* allowance for any of the results which were found in these runs, will not raise this to 10^{-5}. Further analysis of this sideband modulation given in §3.1 will confirm its reality at the 99% confidence level.

2.4 Summary

Since the discovery of the 2.14 ms signal during Feb. '92, 41 more nights' observations were made with the LCO 2.5-m, 5 with the CTIO 4-m, 3 at the European Southern Observatory (ESO) New Technology 3.5-m Telescope (NTT), and 25 with the University of Tasmania (U. Tas.) 1-m, in addition to 5 short observations (two separated by only one Earth occultation) with the HST/HSP, for a total of 78 more observation dates. The 2.14 ms signal was detected in about 11 of the 41 additional LCO 2.5-m nights, about 3 of the 5 CTIO nights, 1 of 3 NTT nights, 2 of the '4' HST/HSP observations, and

[15] The continuously interpolated Fourier spectrum presents more opportunities for peaks to appear than just the finite number of discrete points within a given range, but not infinitely many more, as the spectrum is only free to vary so much between the discrete points.

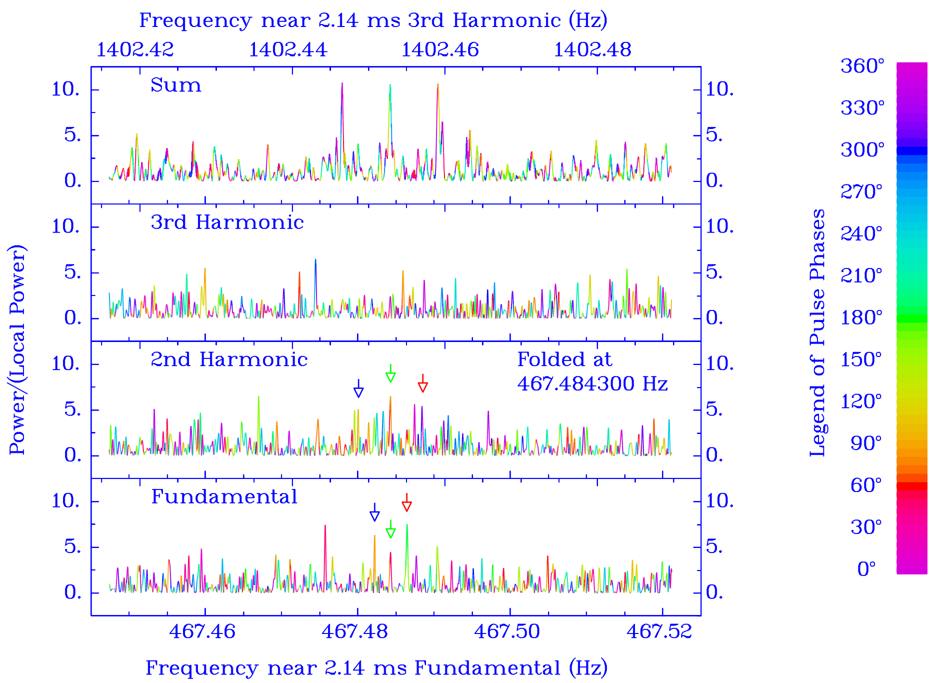

Fig. 2. (Lower three frames) The Fourier power spectra for frequency regions near 467.4843 Hz (close to the Feb. '92 467.4934 Hz frequency extrapolated to Feb. '93) and its first two higher harmonics (the 2nd near 935 Hz and the 3rd near 1402.5 Hz) from data taken at LCO during early UT Feb. 6, '93. (Top frame) The sum spectrum of the fundamental and 2nd harmonic (see Eqn. 1). The arrows point out the peaks in the fundamental and 2nd harmonic spectra which sum to the three high peaks in the top frame.

about 4 of the first 8 U. Tas nights, including two detections in the first three nights' observations less probable than one part in a million, after which no signal was observed in the next 17 nights.

Thus, at the risk of oversimplification, the 2.14 ms signal was seen following its discovery in 21 of the next 78 nights. However, the actual sequence of discovery depended upon a smaller number of stronger detections which collapsed the search space in frequency, for observations made sufficiently close in time to these (within a few days), to allow other detections of lower significance (we assume that peaks in the power spectrum closer to the mean trend in frequency are more probable than those which are farther away). In any case, by the time of the observation of Aug. 23, '93, the probability of the 2.14 ms signal not being real was below 10^{-10} (see §3.2.3). The occurrence of the ~1,000 s modulation, at times significant in its own right, aided the decision-making process involved in the search.

Figure 3 summarizes the estimated ~1,000 s modulation periods, 2.14 ms frequencies, f, the long term $\frac{\partial f}{\partial t}$'s (mean spindowns), and magnitudes for the nights when a 2.14 ms signal appeared during 1992 through early 1996. The

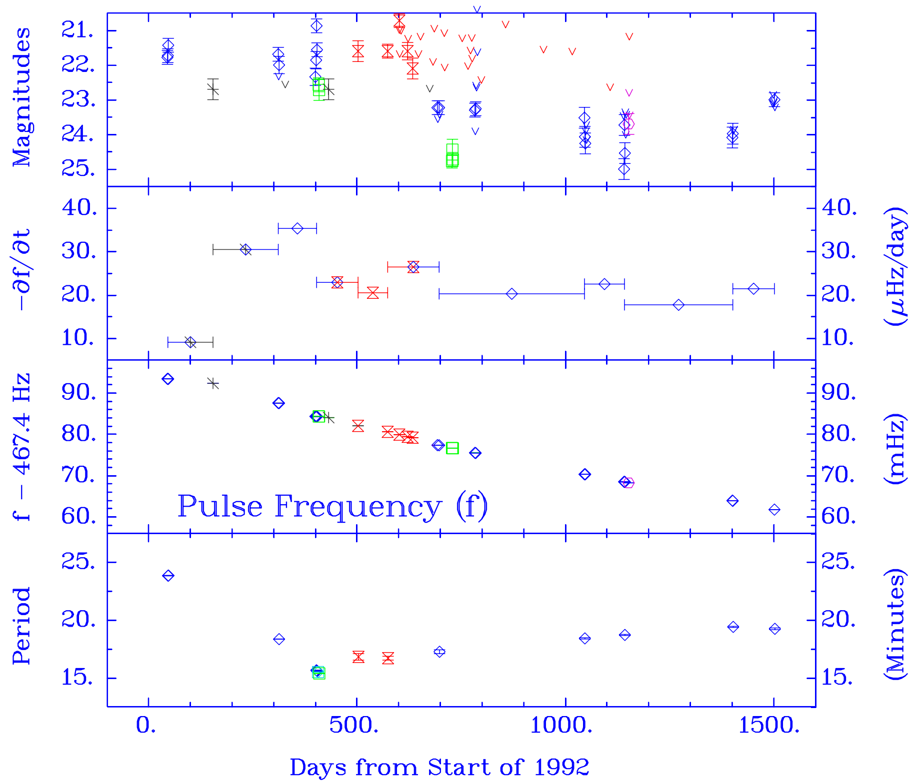

Fig. 3. The time histories of the modulation period (lower frame), the $\sim$467.5 Hz pulse frequency (2nd frame from bottom), the mean $\frac{\partial f}{\partial t}$ for the intervals between detections of the $\sim$1,000 s period (third frame from bottom), and the inferred I magnitude (upper) for points earlier than day 500, V+R+I composite magnitude for LCO and CTIO points afterward, and S20 band magnitude for HST/HSP, Galway/NTT, and U. Tas points. The y axis of the 2nd frame from the bottom represents the difference of the observed frequency and the base frequency listed on the left hand side. The upper limits for the magnitudes in the top frame are plotted as 'v's for all observatories. In all other cases, observations with the LCO 2.5-m, CTIO 4-m, U. Tas. 1-m, HST/HSP, and NTT are represented by diamonds, squares, hourglasses, '+'s with a '\', and hexagons, respectively (the hexagons are barely visible in frames 2 and 4 near day 1150). Points of mean $\frac{\partial f}{\partial t}$, which depend on observations from two separate telescopes, have both symbols plotted.

magnitudes, mean frequencies and modulation periods for the data are listed in Tables C.3-C.5.

The upper limits plotted in Fig. 3 and listed in Tables C.3 and C.4 are derived from the observed magnitudes listed in these tables and from the 2σ magnitudes listed in Tables C.1 and C.2 (see the text of Appendix C for details).

Figure 3 and Tables C.3 and C.4 show that the signal faded dramatically after Sep. '93. Before this time, the results were stronger and more consistent. Afterward the results were weaker, and usually very hard to detect consistently. By the end of Aug. '93, the decline of the 467.5 Hz frequency was sufficiently well established that there should have been no difficulty in locating results near the extrapolated frequency, – there was certainly no difficulty in locating the weak result on Sep. 24 (see Appendix B, Fig. B.3, & §B.2.3). After Sep. '93, the detections of the 2.14 ms signal in a several-hour observation occurred only for the most sensitive observations. Among these are the detection with the CTIO 4-m on Dec. 30 '93, and the three detections out of six nights from the Nov. '94 LCO 2.5-m observations, the only clear multiple-night detection in that epoch.

3 Further Sideband Analysis and Data Issues

3.1 The Nature of the Sideband Modulation

A periodic signal can be harmonically modulated in only two fundamental ways, each of which has a characteristic pattern of sidelobes in the Fourier spectrum, centered about the mean frequency of the signal. For harmonic amplitude modulation (AM) with a given frequency, Ω, and a fractional amplitude, α, the effect on the expected count rate, $< R(t) >$, due to a given harmonic frequency of a pulsar, ω, with amplitude, a counts/s, is given by:

$$< R(t) >= R_o \; + \; a\{1+\cos(\omega t+\phi)\}\{1+\alpha\cos(\Omega t+\psi)\} \qquad [counts/s]\,; \quad 0 \le \alpha \le 1, \tag{2}$$

where R_o is the count rate in the absence of the pulsar signal, t is time, and ϕ and ψ are arbitrary phases. In the Fourier spectrum of such a modulated signal only two sidelobes (each with $0.25\alpha^2$ of the power of the main peak) appear at frequencies, $\omega \pm \Omega$, i.e., displaced symmetrically about the main Fourier peak at frequency, ω. The effect of the modulation on the time-averaged component of the pulsar signal (at the usually very low frequency, Ω) will be undetectable because of low frequency noise if a is small.

In the case of harmonic modulation of the phase of the periodic signal (i.e., FM, or frequency modulation), the expected count rate is given by:

$$< R(t) >= R_o + a\{1+\cos\left(\omega t+\phi+z\cos\left(\Omega t+\psi\right)\right)\} \tag{3}$$

$$= R_o + Re\{a\left(1+e^{i(\omega t+\phi \; + \; z\cos(\Omega t+\psi)\;)}\right)\}$$

$$= R_o + Re\{a(1 \; + \; e^{i(\omega t+\phi)}(1+iz\cos(\Omega t+\psi)$$
$$-z^2\cos^2(\Omega t+\psi)/2 - iz^3\cos^3(\Omega t+\psi)/3! \; + \; \cdots)\}, \tag{4}$$

where z is the amplitude of the phase modulation, in radians. In this case a family of symmetric sidelobes appears in the Fourier power spectrum at frequencies of $\omega \pm k\Omega$, $k = 1, 2, \cdots, \infty$, and whose powers are proportional to ${J_k}^2(z)$, where J_k is the k^{th} Bessel function of integer order. For phase modulation with amplitude of a radian or smaller, only the central peak at frequency, ω, (whose power scales as ${J_0}^2(z)$), and first sidelobes at $\omega \pm \Omega$, have significant power. For phase modulations of larger amplitude it is possible that no power remains at the central frequency.

In order to analyze the data for the presence of such modulations, modulation *spectra*, spanning a wide range of modulation frequency about a peak at a central frequency, ω_o, with phase, ϕ_o, can be generated as follows:

$$a_{AM}(\Omega) = \{e^{-i\phi_o}a(\omega_o + \Omega) + e^{i\phi_o}a^\dagger(\omega_o - \Omega)\}/\sqrt{2}; \quad (5)$$
$$a_{FM}(\Omega) = -i\{e^{-i\phi_o}a(\omega_o + \Omega) - e^{i\phi_o}a^\dagger(\omega_o - \Omega)\}/\sqrt{2}. \quad (6)$$

All features due to amplitude modulation *and* all *even* order ($k = 2, 4, \cdots$) phase modulation features in the Fourier spectrum will appear in (project into) the actual amplitude modulation spectrum constructed as described in Eqn. 5 above. The *first* (i.e., $k = 1$) and all other *odd* order phase modulation peaks will project into the phase modulation spectrum when constructed as described in Eqn. 6 above. Thus, aside from noise, only true phase modulation will appear in the phase modulation spectrum

Such a standard AM/FM sideband analysis (Middleditch et al. 1981) of the central peak for the $\sim$ 467.5 Hz fundamental frequency detected on Feb. 6, ‘93, indicated a significant phase modulation of the fundamental frequency (Fig. 4), with an amplitude of 1.6(+0.3,-0.5) radians, or 90 degrees of (harmonic) phase shift every $\sim$467 s (the ratio of the power in the modulation peak to that of the central peak scales as $2(J_1(z)/J_0(z))^2$, where $z \sim$1.6 for this case). A similar analysis of the same data set for the dozen most significant noise spikes found between 108 and 1,840 Hz showed no statistically unusual sideband feature.

Although 90 degrees of phase shift or pulse time-of-arrival (toa) modulation is close to (or exceeds) the maximum of the harmonically varying pulse time delay/advance which can be produced in a *single-peaked* pulse profile by pulsar precession (Nelson et al. 1990), a 90 degree modulation in the phase of the fundamental can also be produced via precession through alternate modulation of the *strengths* of the two peaks of a double-peaked pulse profile, much more readily than it can by pulse toa modulation. As an example, it is simple to imagine a precessing body having a periodic “dipping” motion causing a slightly more favorable emission geometry in one beam, which originates from magnetic field lines from one pole, while having exactly the opposite effect on the beam from the other pole. (For a toa modulation greater than 90°, on the

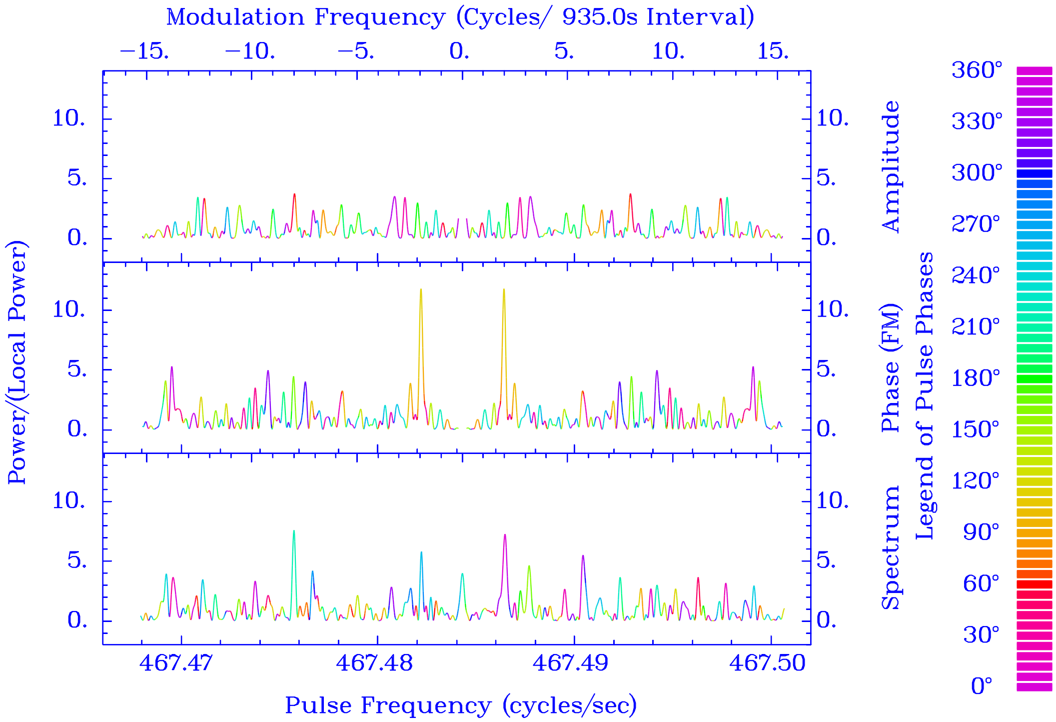

Fig. 4. (Bottom frame) the Fourier power spectrum near the 467.5 Hz fundamental frequency for data taken on UT Feb. 6, 1993. The peak in the center of this lowest frame, underneath the '0' major tick mark (at the top center of all of the frames), is the feature being analyzed for sideband modulation. (Middle) The FM-sideband modulation spectrum (Eqn. 6) of the peak near 467.48429 Hz in the bottom frame. (Top) Its AM-sideband modulation spectrum (Eqn. 5).

2nd harmonic of the ∼467.5 Hz signal, see Appendix B, §B.3.1).

The sideband analysis of the second harmonic (Fig. 5) shows four modulation peaks, three in the amplitude modulation spectrum and one in the phase (frequency) modulation spectrum. Two of these peaks occur at the 1st and 2nd multiples of ∼1/(467 s) (of which only the latter contributes to the sidelobes in the sum spectrum of Fig. 2), and two others occur at the 1st and third half multiples (*neither* of which contributes to the sidelobes in the sum spectrum of Fig. 2), indicating an actual modulation period of ∼935 s. These three "extra" peaks in the modulation spectrum of the 2nd harmonic lend credibility to the interpretation of the modulation as a real phenomenon.

Summing the power in the six possible locations (determined blindly, as the 935.2 s modulation period used was derived from very high harmonics – see note 'h' to Table C.5) where sub-harmonics could have appeared within the (4th) harmonics of the 1/935 s periodicity which bound the frequency range of the discovery, gives some 18.5 times mean power for a probability near

0.0002. Of course, the pattern in which peaks only appeared in the amplitude and/or phase modulation spectra at $(1/2)\times 4/(935 \text{ s}) = 2/(935 \text{ s})$ would also have been admitted (but *not* for (1/3) and $(2/3)\times 4/(935 \text{ s})$, and all other odd denominator fractions, as this would imply that the modulation on the 467.5 Hz fundamental would *not* be an integral harmonic of (1/935 s)).

It is unlikely that other patterns, with peaks outside of the 4/(935 s) modulation on the second harmonic, would also have been admitted, unless modulation at 2/(935 s) confirmed the pattern. The measure of unlikelihood of such an outcome as shown in Fig. 5, given a handful of admissible patterns, each of low probability, $P_k,\ k = 1, \cdots n$, is given by

$$Prob \ = \ 1 \ - \ (1 - P_1)(1 - P_2) \ \cdots \ (1 - P_n) \ \sim \ \sum_{k=1}^{n} P_k. \qquad (7)$$

Even taking just the power in the modulation spectra at 2/(935 s), 6.97 instead of the full 18.5, yields a probability less than 1%, which seems a reasonable and conservative upper limit for the sum of the handful of terms on the far right of Eqn. 7. So again the probability of accidentally seeing such a pattern which would have been recognized as a valid modulation of the 2.14 ms signal is multiplied by another small factor.

By folding the data modulo the 2.14 ms period into 8 separate pulse profiles, one each for the 8 contiguous sub-intervals of each of the five full ∼935 s time intervals in the Feb. 6, '93 data, to make a "movie" of the pulse profile modulo the 935 s period (∼117 s in each sub-interval, with the profile in each of these receiving contributions from five, identical mod 935 s, sub-intervals), the changes in the pulse profile which give rise to the complicated modulation spectra of Figures 4 and 5 are rendered visible in Fig. 6.

As expected, the alternating double pulse effect shows up clearly in Fig. 6 (lower three frames). Although such changes seem innocuous, their effect on the modulation spectrum, aside from producing the 467 s phase modulation sidelobes in the Fourier spectrum near the fundamental, is to put power in the 8th and higher harmonics of the 935 s modulation, as there is no way that simple, low harmonic phase or amplitude modulation can produce these changes. Then the signal is basically absent from the fourth and fifth frames, a sudden change which again throws power into the higher harmonics of, this time mostly, the AM spectrum.

Significant pulse profiles return to the upper three frames, and again the *difference* between the 7th and 8th frames is significant, but can be rendered statistical by shifting the 7th frame by 3-5 frames. This causes some power to appear in the lower harmonics of the 935 s modulation spectrum. By contrast, the difference between the 8th frame and the 1st, the most significant

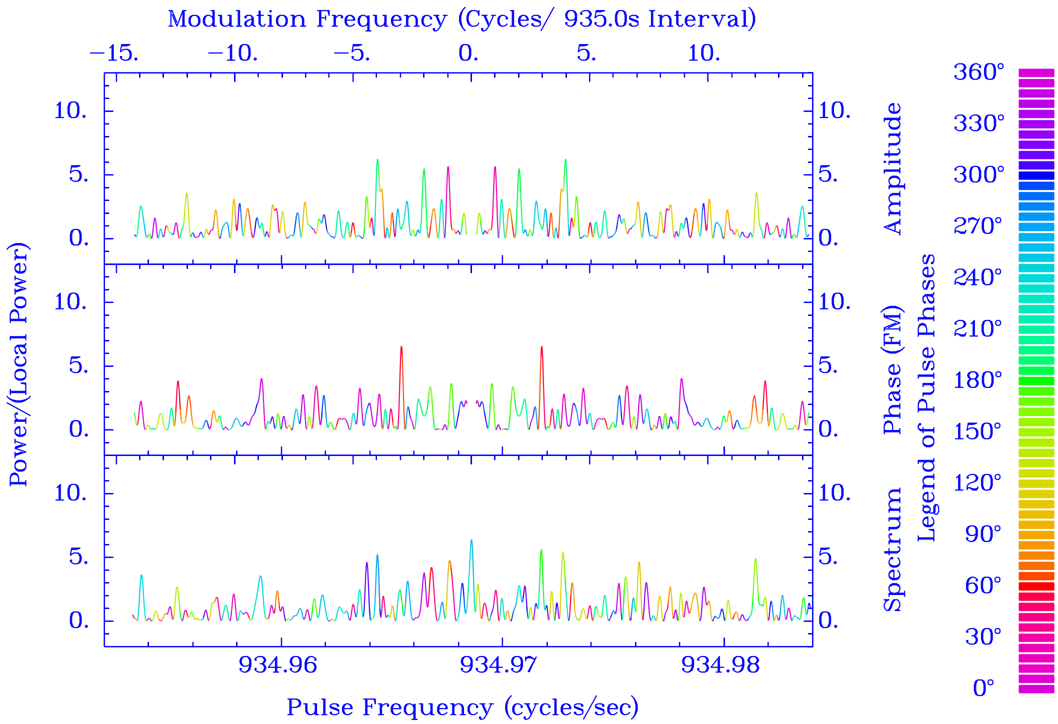

Fig. 5. (Bottom frame) the Fourier power spectrum near the 935 Hz second harmonic frequency for data taken on UT Feb. 6, 1993. The peak being analyzed for sideband modulation is the one in the center of this frame. (Middle) The FM-sideband modulation spectrum of the peak near 467.48429 Hz in the bottom frame. (Top) The AM-sideband modulation spectrum of the same peak.

of all such differences, can be reduced to insignificance by a phase shift (an advance[16] from the 8th to the 1st frame) of only 2 bins, or 1/8th of a cycle (and thus mostly puts power into the very lowest harmonics of the 935 s modulation spectrum). In §4.1.1 we argue that this phase advance is consistent with free precession of an oblate body.

The remainder of the data from the Feb. '93 observing runs was then searched for the 467.4843 Hz peak in the coherent sum of the fundamental and 2nd harmonics (see Eqn. 1). Evidence was found for this signal in data taken on the three other nights at LCO (early on UT 3, 5, and 7 Feb. '93). The signal had faded by the 11th of Feb. – the first of two nights on the 4-m at CTIO – but was still sufficiently strong (I∼22.57) to produce a weak confirmation (Fig. 7). It continued to fade slightly by the next night (I∼22.72), when more and better quality data were obtained.

[16] An earlier pulse arrival results from a higher frequency, and thus has a more positive *timing* phase. This is opposite the sense of the "pulse phase" plotted on the abscissa in Figures 1, 6, B.1, B.3, B.5 and B.7.

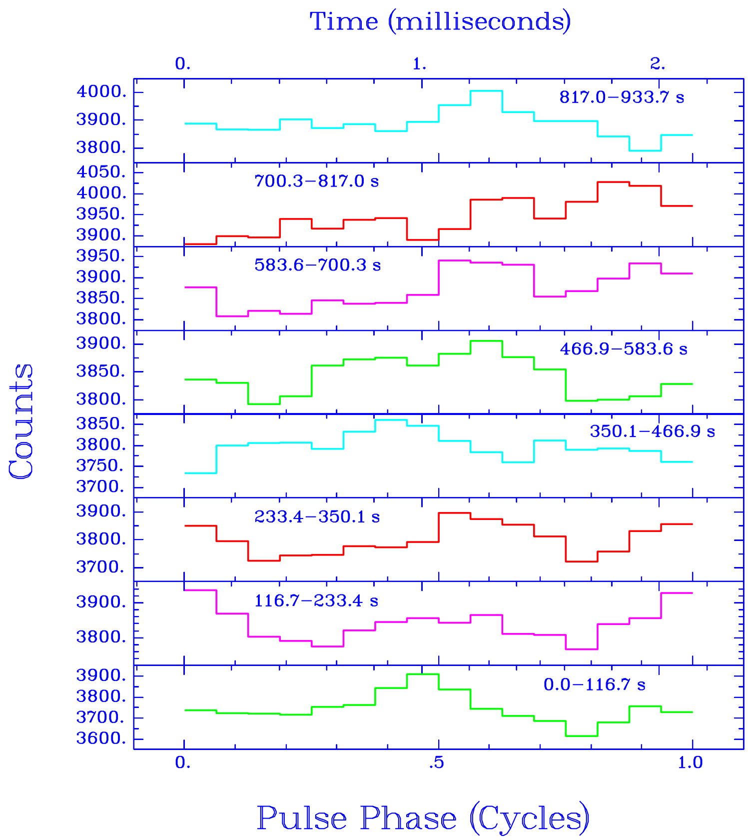

Fig. 6. An 8-frame movie (running upward) of the evolution of the 2.14 ms pulse profile as constructed modulo eight sub-segments of each of the five whole ∼935 s modulation periods in the data taken on Feb. 6, '93 (a 933.7 s period was used for numerical convenience).

We then re-examined the Feb. '92 data and found evidence for the first and third harmonics of a 1430 s phase modulation on the three of four strongest harmonic components of the 467.4933 Hz signal in the data from each night – the fundamental for both Feb. 15 and 16, and the 2nd harmonic for the latter date. However the implied phase modulation was nowhere near as extreme as that shown in Figures 4 and 5, and this is consistent with the relatively sharp pulse profile for this data as seen in Figure 1. By contrast, the pulse profile from the Feb. 6 '92 result, the sum of the eight profiles shown in Fig. 6, is quite broad. It is worth emphasizing that this does *not* have to happen. There is no reason why unrelated power, removed from a central peak by several Fourier spacings, and which appears to be sideband phase modulation but really isn't, will prevent the pulse profile of the central peak from having its own rich harmonic structure and, in consequence, being narrow. Conversely, compensating a signal for the phase modulation implied by unrelated sideband power will not necessarily sharpen the pulse profile (but if it *does* sharpen, it may be taken as good evidence that the sideband power *is* related – see Appendix B, §B.2.1 & §B.3.2).

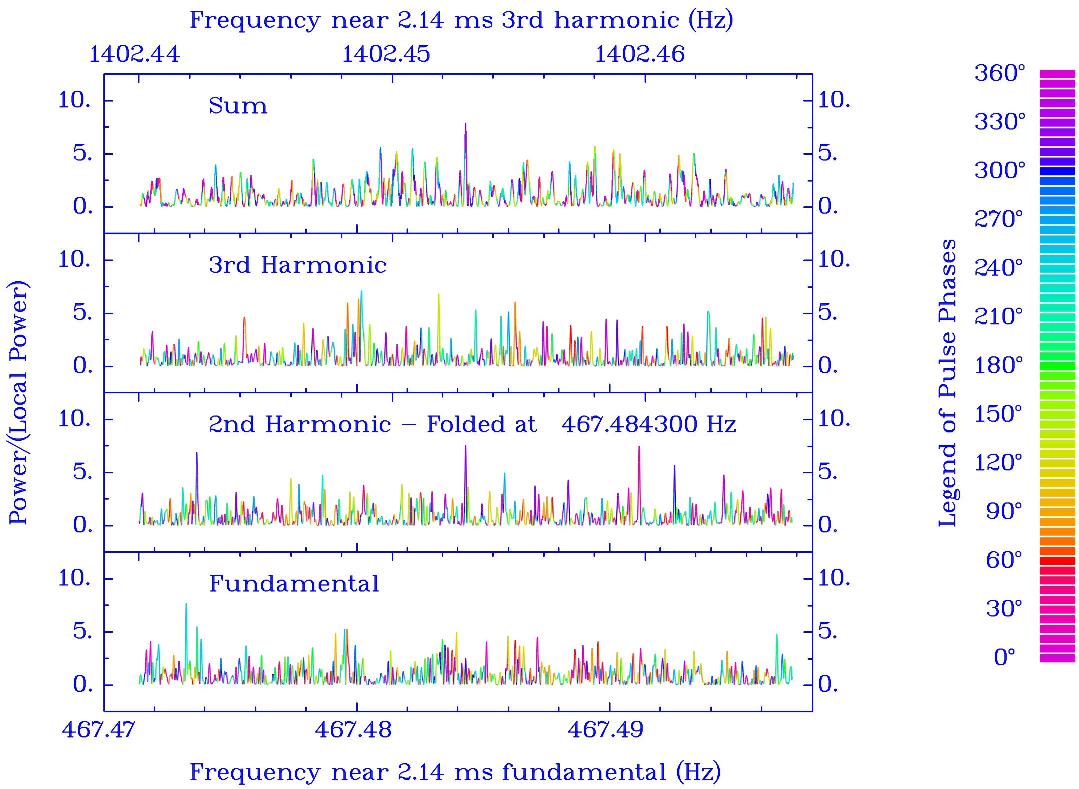

Fig. 7. The individual and harmonic sum spectra for data taken on the CTIO 4-m telescope on Feb. 11, '93 (as done in Fig. 2).

3.2 *On the Reality of the 2.14 ms Signal*

3.2.1 *Possible Sources of Contamination*

Time series optical astronomy does not have the myriad of sources of contamination that plague longer wavelength bands, mostly because the data are taken in single photon pulse counting mode. The signals seen from LCO, CTIO, HST/HSP, Tasmania, and the NTT did not have many obvious contaminants in their Fourier spectra. At LCO, after about February, 1994, a 2.5000 Hz signature resulted from using piezoelectric means to move the secondary mirror in order to guide the telescope. This signal, at times, showed higher harmonics (but 2.14 ms would have to correspond to the 187th, 374th, $\cdots$, harmonics of this signal).

In addition, for SN1987A to be properly centered within the 3.77 arc s aperture used, it was necessary to include part of star number 3 (see, e.g. West et al. 1987). An error in the drive gear of the Dupont 2.5-m (there is hardly a telescope which does *not* have such an error) caused this star to dither in an east-west manner with a period of a few (likely sidereal) minutes, so low in frequency that the ordinary Fourier analysis usually made no mention of it.

One way that contamination can enter the pulse stream is if the discriminator amplifier, which takes the signal from the nearby phototube, has contaminating frequencies, such as 60 or 120 Hz. These were never seen (though these may have occurred at 50 Hz for an earlier report at another observatory), in spite of data taken on bright, confused sources, such as the center of the globular cluster, M15. The signal cable from the phototube to the discriminator was only one foot in length, and although the cable from discriminator to the recording system was 100′ long, it was RG223, and hence, doubly shielded and the pulses passed through it without obvious distortion or contamination.

Other possible contamination, where only a constant, but very small contribution of counts might periodically leak into the pulse stream, are contra-indicated by runs with fewer counts than usually gathered on SN1987A ($\sim$270/s with the narrow filter and about ten times that with the broader filter). This possibility is harder to guard against, as the runs on weaker sources generally didn't last as long as runs made on SN1987A. The cold dark count from the phototube was well under 1/s, and could not have produced the results seen even if it were entirely pulsed. Thus the source of such contamination would likely have to be optical. The best contra-indication of this are the results seen at other observatories/telescopes and data recording equipment, where no obvious contamination was seen.

3.2.2 The Early Results from LCO and CTIO

The probability analysis presented above for the consistent picture of the modulation led to a confirmation of the 2.14 ms signal, as first seen during the Feb. '92 observing run, at the level of 1 in 10^5 as of Feb.'93. Structure observed within this modulation led to another small factor of 1 part in 10^2 which multiplies this already small probability of the signal being due to statistical fluctuations.

3.2.3 The Results from Tasmania and HST/HSP

Out of the first eight nights' observation of SN1987A with the U. Tas. 1-m there were three definite and two other possible weak detections of the 2.14 ms signal at a level between 20.7 and 22.3 magnitudes, after which no definitive results were obtained in the remaining 17 observations.[17] Plausible 2.14 ms signals were also detected at magnitude 22.7 in June, '92 and March, '93 HST/HSP data sets, both obtained during an epoch when results on the 2.14

[17] The less probable of the 17 nondetections were also searched for definitive sideband modulation, with null results – see Table C.4.

ms signal were most consistent. The details of these observations are given in Appendix B §B.2.

Viewed as confirmation of the 2.14-ms candidate pulsar signal the four consecutive detections which followed the Feb. 93 observations from LCO and CTIO, one with the HST/HSP on March 6th, and the three following on May 16th, July 26th, and August 23rd, represent a sequence with a very low probability of all being due to noise. Extrapolating from Feb. 11, '93 to March 6 (23 days) using a derivative of -2×10^{-10} Hz/s (a compromise between no derivative and the actual Nov. '92 to Feb. '93 spindown), we predict an event at 467.48390 Hz (the actual event occurred at 467.484065 Hz, only some 165 μHz higher) with an uncertainty equal to the entire amount of change, or ±400 μHz. This is about only one Fourier spacing for the 2400 s total for this data (there were actually two 1200 s segments separated by one HST orbit, but this only causes redundancies in any Fourier spectrum which includes the gap). Using the third harmonic for the mean harmonic content of the data and a fineness factor of 3.0, predicts an extrapolation uncertainty of only ±27 possible trials for a probability of less than 0.078 of accidentally seeing such a result (again, as stated in Appendix B, §B.2.4, a statistically unusual signal was apparent when the *first* trial was made on this data at a reasonably extrapolated frequency). Proceeding to May 16th still using a 100% uncertainty in the frequency derivative of 2×10^{-10} Hz/s (the extrapolation is actually nearly twice as close than the predicted ±1.2 mHz uncertainty), the second harmonic as the mean harmonic of this more limited data, a factor of 3 for fineness again, and the geometric mean probability between sideband modulation being included or not, gives a probability of 0.075. Proceeding again to July 26th (a 71 day time gap, just as before) and still allowing the same uncertainty in $\frac{\partial f}{\partial t}$ (the extrapolation is again nearly twice as close) gives probability of only 3.3×10^{-5}, while proceeding on to Aug. 23 again using conservative assumptions (even allowing a mean harmonic content of 3, a fineness factor of 3 again, and not even using the very low probability associated with 2nd segment of this data set) yields a probability of only 0.063. The probability that all these events were due to noise is low, 1 in 8×10^{7}, and would still be low even giving up a factor of 10 in *each* of the component probabilities. An estimate extrapolating first to the July 26 result, and then back-interpolating to the May 16 and March 6 results, and extrapolating again to the August 23 result, would give similar, or even less probable results (in this case the uncertainty in the spindown can probably be reduced). Given the nearby sideband structure also evident in at least two of the four events, most of which was not factored into these individual probabilities, the estimate of likelihood would be smaller yet, although much more difficult to quantify.

Of course, given that the signal faded after Sep. 1993, one could dilute the probabilities quoted above. However, the fact that the results from the small telescopes became persistently negative during the epoch when the signal was

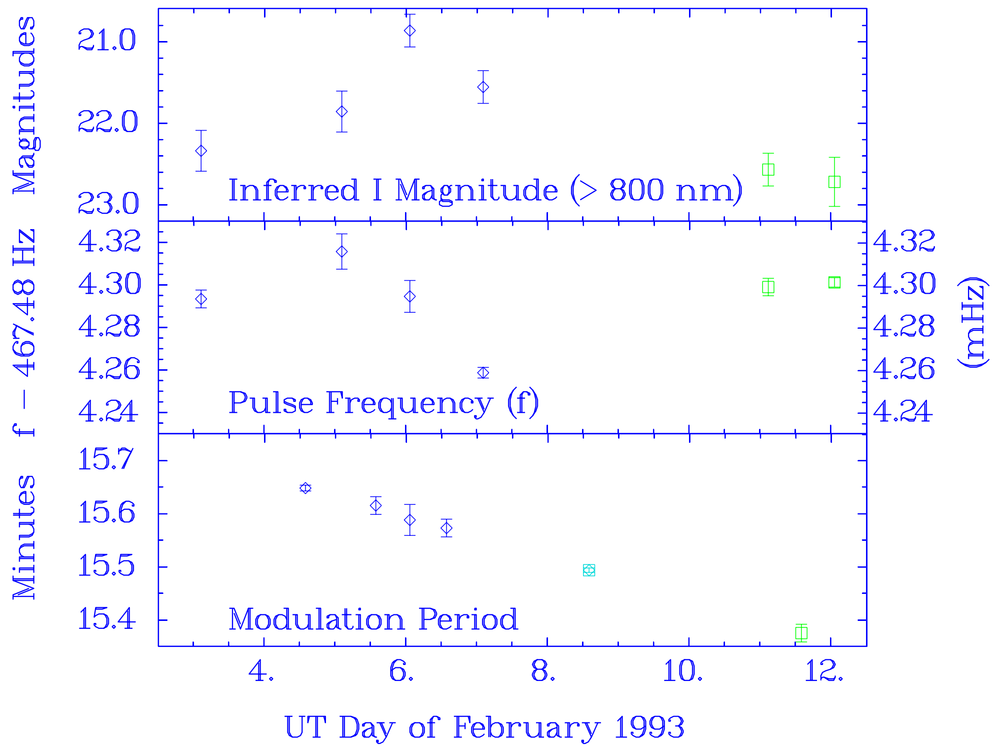

Fig. 8. The time histories during Feb. '93 of the ~1,000 s modulation period (lower), ~467.5 Hz pulse frequency (middle), and the inferred I magnitude (upper). As in Fig. 3, the y axis of the middle frame represents the difference of the observed frequency and the base frequency listed on the left hand side.

faint, but sometimes detectable in the larger telescopes, invalidates such an approach. There is no reason why a signal from SN1987A couldn't fade, given the environment through which it has to shine (Pinto 1999).

3.3 Further Data Issues

3.3.1 Decrease of the ~1,000 s Modulation Period

The modulation periods for the data were first estimated from the harmonics of the modulation for a given night (as, e.g., in the Feb. 6, '93 data), and then further refined by cycle-counting, just as in conventional pulsar timing analysis, between like modulation peaks of pairs of observations (by then it was also known that this period had been previously decreasing – see §3.1). Figure 8 details the estimated magnitudes, frequencies reduced to the center of mass of the solar system (its barycenter), and modulation periods for the data from Feb. '93.

The decrease of the modulation period is at first unnoticeable in Feb. '92, but has a consistent refinement solution (made by counting cycles of the $\sim$935 s period from night to night) with a decrease of nearly 2.4 s/day by Feb. '93 (Table C.5). However, it is difficult to prove that the cycle-counting refinement of the modulation periods for the extended interval during Feb. '93 is unique, as, e.g., each period derived for observations spanning N days has other almost equally good values spaced at intervals of $\sim 935/((\mathrm{N}\times 86400/935 \sim \mathrm{N}\times 90) \pm 1) = 10.4/\mathrm{N}$ seconds. Thus refinement solutions, with the period stationary or increasing, might be possible. On the other hand, it might also be possible that the modulation period declined *faster* than indicated in Fig. 8. In any case, there is little doubt that the modulation period was near 935 s for this data, and reasonable evidence that the period for the Feb. and Nov. '92 data was near 1,430 and 1,100 s respectively (see §3.1 and Appendix B, §B.1).

3.3.2 Spindown Issues

Considering again the Feb. '92 data, it was puzzling that none of the candidate spin-downs listed in Table 1 matched the apparent night-to-night decline in the three frequencies, a loss of about 9 μHz/night (see Table C.3, and footnote 'd'). This rate of decline apparently persisted at least until June 2nd, when a result was obtained from the HST/HSP at 467.4923 Hz. However, folding the Feb. '92 data with the first and third harmonic phase modulation implied by the 1430 s sideband pattern, which dominated in the stronger data from Feb. 15 and 16, produced results which were consistent with the observed night-to-night spindown, and a pulse which was much sharper than that shown in Fig. 1, and, of course, more significant due to the modulation power incorporated.

Before leaving the discussion of the 1430 s modulation of the Feb. '92 data, it is worth noting that, for a while, shortly following the discovery of the $\sim$1,000 s modulation, the phase of the 1430 s modulation for Feb. 16, '92 was in error by 180°. Until this error was corrected, it was *impossible* to unambiguously determine the number of 1430 s cycles between this night and the previous night, let alone recover such a sharp signal by folding. In a similar vein, the data taken during Nov. '94 were initially analyzed incorrectly by using the ephemeris for PSR0540-69 – some five minutes later on the sky than that for SN1987A. The significance of the 2.14 ms signal in all three nights with detections from this run increased slightly when reduced with the proper ephemeris. Finally, the phase demodulated results for Feb. 7, '96 were also tested without correction to the solar system barycenter. The corrected results were always more significant (see Appendix B, §B.3.2).

3.3.3 *The Statistics of Weak Modulated Signals*

For a Fourier spectrum in which a rich spectrum of modulation such as that depicted by Figs. 2, 4, 5 and 7 is weakly present, the peaks which are both: (1) members of the complicated patterns described above, and (2) also visible to one observer, most probably are those which added *in phase* with that particular observer's noise (this may explain the apparently successful timing of the modulation period during Feb. '93 shown in Fig. 8). The set of peaks visible to another observer may show little overlap with the first observer's set, as the noise spectrum experienced by each observer will differ, but the peaks of the modulation spectrum that *both* detect should agree in phase. For the moment, we can only sketch what appears to be a consistent *pattern* which must be checked as such, rather than demanding that all details reproduce exactly.

4 Discussion

4.1 *Timing Behavior*

Taken at face value, the evidence that the 2.14 ms periodicity is a real phenomenon is strong. After four years of effort, there is also strong evidence that the signal is not due to contamination. If so, then the compact remnant of SN1987A is (at times) an *optical* ms pulsar with an enormous mean, and non-uniform spindown which increased for the interval between Feb. '92 and Feb. '93, and again for the interval between Nov. '95 and Feb. '96, and a sideband modulation spectrum with one period near 1,000 s which was dropping precipitously in the first interval, and perhaps with other modulation periods.

4.1.1 *The Case for Precession and/or r-mode Instabilities*

The regularity of the timing of a pulsar can be affected by a number of causes. Among these are accelerations due to the periodic orbital motions of gravitational companions (Wolszczan & Frail 1992), glitching, or abrupt changes in the spin frequency due to settling of the stellar crust or changes in vortex pinning in the interior, coupling to differential rotation, and neutron star precession. Also, if, somehow, instead of rotation, neutron star vibration or oscillations are responsible for the dominant periodicity, then sideband periodicities and other instabilities are also possible.

Whatever physical cause is assigned to the $\sim$1,000 s modulation of the 2.14 ms signal, it must explain the observed behavior of the periodicity. This includes its ability to produce modulation which appears to mimic a time-of-arrival modulation of the 2.14 ms pulse, as seen, e.g., in Figs. B.1 and B.7, where the effect is proportional to the harmonic number. It must also explain other kinds of very complicated modulations where the effect is not proportional to the harmonic number, as shown in Figs. 4-6, and where it also includes modulation of the amplitude of the signal as well. In addition, there must be a way for the modulation to couple to the optical pulsations. Finally, it must explain the occasional doubling of the modulation frequency.

Although glitching is now known to occur in a number of pulsars, it has never been shown to produce strong, short-term periodicities, such as the ~1,000 s modulation. Thus glitching, and for the same reason, crust settling, are unlikely sources of the modulation periodicity of the 2.14 ms signal. Moreover, strong harmonic structure, as occurs in the 2.14 ms signal, is not generally associated with neutron star oscillations, thus oscillations are an unlikely source of the 2.14 ms periodicity. It is also difficult to see how neutron star oscillations can couple to the generation of the pulse profile to produce the modulation periodicities. A similar case can be made against the ~1,000 s periodicity being due to differential rotation, although this could certainly cause some of the observed, non-periodic behavior of the 2.14 ms signal.

Gravitational companions can produce periodic modulation of the times of arrival of a pulsar signal, and in certain cases, modulation of the amplitude of such a signal when the pulsar signal is eclipsed. However, the effect of a modulation of the times of pulse arrival would produce a phase modulation, in, e.g., radians, which is strictly proportional to harmonic number (see §3.1). This is not what is evident in Figs. 4-6, where the amount of phase modulation is greater for the fundamental frequency than it is for the second harmonic. It is also difficult to see how planetary orbits can double the frequency of the modulation.

The simplest way to produce the modulation observed in Fig. 6, as argued in §3.1, is via precession (Nelson et al. 1990, Pines & Shaham 1972a,b). Precession can produce both time-of-arrival (toa) and non-toa modulation of the pulse profile via the wobbling motion involved and by periodically rendering parts of the pulsar beam visible and invisible. Precession can double the frequency of the modulation when the line of sight becomes perpendicular to the mean axis about which the pulsar wobbles.

Finally, the similar steepening in the declines of the 2.14 ms and 1,000 s periodicities (Fig. 3) also argues in favor of precession, and gravitational radiation, the nearly inevitable result of the quadrupole moment necessary to cause the precession, as the source of the decline of the 2.14 ms (spin) period. Since the braking index (n – Appendix A) is sometimes negative (Fig. 3), it can not be used to confirm or refute the suspected GR-dominated spindown. Indeed, if the erratic behavior of this pulsar is typical, then an epoch wherein the pulsar's spindown is both dominated by GR and sufficiently stable to reflect this in its braking index may *never* exist. The barely noticeable departure from linearity of the frequencies shown since mid-'93 until '95 in Fig. 3 corresponds to a braking index near +4,000.

However, if the apparent precession is a result of the *same* non-axisymmetric oblateness (relative to the axis of rotation) which drives the apparent spindown, then we have:

$$\Omega_{prec} \propto \frac{\delta I}{I}\omega_{spin}; \quad \frac{\partial \omega_{spin}}{\partial t} \propto (\delta I)^2 \ , \tag{8}$$

where ω_{spin} is the rotational frequency of the pulsar, Ω_{prec} is the precession frequency, I is the moment of inertia of the (precessing part of) the neutron star, δI is the non-axisymmetric contribution to I, and $\frac{\partial \omega_{spin}}{\partial t}$ is the spindown. Combining these gives,

$$\frac{\partial \omega_{spin}}{\partial t} \propto \Omega_{prec}^2 \ . \tag{9}$$

Thus the GR hypothesis can be tested by plotting the spindown against the square of the reciprocal of the modulation period, as shown in Fig. 9. Gravitational radiation from a neutron star with a moment of inertia, I, constant to within a few percent, would produce points which lie along a straight line which passes through the origin. With the exception of the Feb. '92 data, whose spindown was (necessarily) taken from the interval to the June '92 HST/HSP result, the spindowns were derived from the mean spindowns which *preceded* each group of observations with a measured modulation period.

An early estimate (Pandharipande et al. 1976) for the possible triaxiality, $\sim 10^{-6}$, as well as a similar value for Her X-1, which is also thought to precess (Trumper et al. 1986, however, Priedhorsky & Holt 1987) are both consistent with what is observed in the 2.14 ms signal. Subsequent work intended to explain the *lack* of such in "normal" ms pulsars with small $\frac{\partial p}{\partial t}$'s reduced the estimate of this number by orders of magnitude using arguments invoking the much lower density near the neutron star surface (Alpar & Pines 1985), but also gave an estimate of $\sim$1,300 yrs for the times over which such triaxiality can persist without vortex pinning. Given this, it is entirely unnecessary to restrict the triaxiality to the very low density exterior of the crust, particularly considering also that the propagation of cracks through the crust due to stresses will eventually cause it to settle with time.

In addition, as the strength of the crust increases with density, it is plausible that the *entire* crust can sustain an initial non-axisymmetric oblateness of

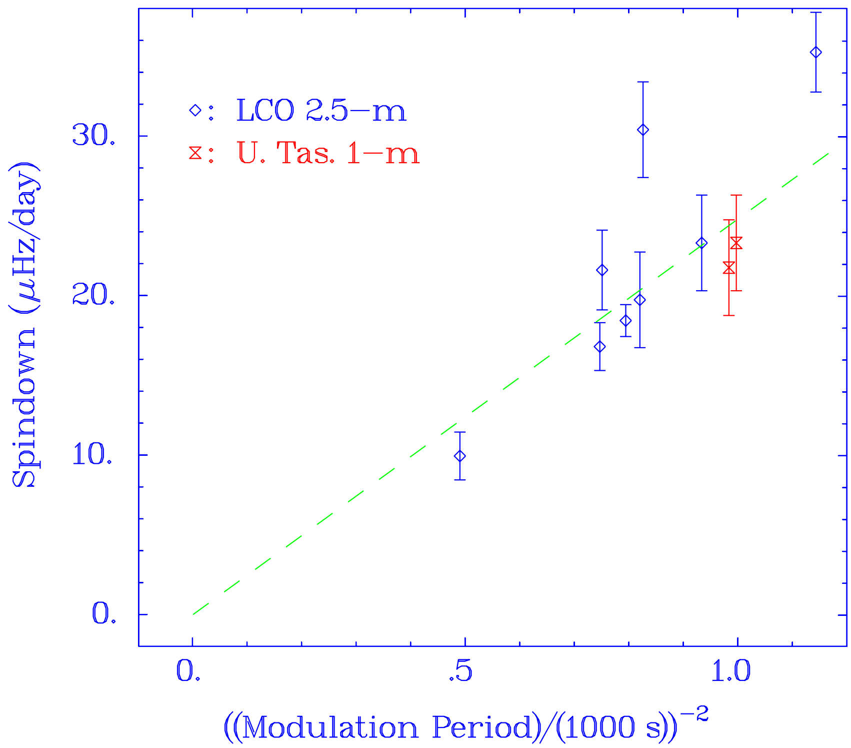

Fig. 9. The spindowns of the detections of the 2.14 ms pulsations with detectable ∼1,000 s modulations are scattered against the reciprocal of the squares of the same modulation periods.

$\sim 10^{-6}$. If the crust is the *only* part of the star participating in the precessional motion, then the observation of a ∼1,000 s modulation period for the 2.14 ms signal is perfectly reasonable. If the crust holds some 25% of the stellar moment of inertia (a higher value than most current models of neutron star structure would allow) the numbers are still reasonable, even if the rest of the star should couple to the precession. Moreover, a 1,300 year timescale for damping of this motion is consistent with the behavior of the compact remnant at 5-9 years of age implied by the 2.14 ms signal (see §4.1.2 below for further discussion).

Finally, recent work (Owen et al. 1998, Lindblom et al. 1998) indicates that an r-mode instability, which may be present in hot young neutron stars, is capable of producing copious amounts of GR, in addition to mimicking the effects of precession. This instability is only expected to operate during the first year or so, before the neutron star interior cools to 10^9 K, by which time it has slowed the neutron star rotation to 100 Hz, or below. However, PSR J0537-6910 in the LMC remnant, N157B, was probably spinning at a rate of at least 140 Hz at one year of age, so perhaps the instability does not radiate the neutron star's angular momentum quite so efficiently, and also, perhaps, the time duration over which it operates may exceed a decade.

In §3.1 we discussed the evidence in Fig. 6 which may favor free vs forced precession. In free precession of an oblate body, the body rotates around the angular momentum vector with main spin frequency, ω, while rotating in the opposite sense about its symmetry axis at the precession frequency (Shaham 1986). Thus the "wobbles" of free precession should subtract from the ~467.5 Hz frequency, and the dominant *observed* rotation frequency, which originates from the magnetic moment of the star, should be the difference of the two frequencies. If this is the case for the 2.14 ms signal, then the phase advance from 8th frame to the 1st frame of Fig. 6, modulo the 935 s period, is consistent with free precession of an "effectively" oblate body, one where the eigenvector corresponding to the largest eigenvalue of its inertia tensor is closest to its spin vector. The remaining four significant frames in Fig. 6 would indicate that the frequencies usually do subtract, with upper sidelobes dominating only sporadically (but appearing more frequently than lower sidelobes), again consistent with free precession. When all the evidence is considered, there could be a slight preponderance of upper vs lower sidelobes, including power just higher than the fundamental frequency, though this is not evident just from Table C.5.

4.1.2 Spindown Irregularities

The lack of a persistent spindown in the 467.5 Hz frequency during our observations of Feb. '93 would be troubling if it were not for the detection of a 467.48406 Hz signal in HST/HSP data from 6 March. The HSP observation followed our observations by only three weeks, and is consistent with a stationary period persisting for at least half of the intervening interval. An extrapolation of the Feb. '93 frequency to March 6 using the steep spindown characteristic of the Nov. '92 to Feb. '93 interval would predict a frequency of 467.4837 Hz, significantly lower than (but still only one resolution element away from) that actually observed. The first three nights of the Nov. '94 run also showed no mean spindown (see Table C.3). The decline of the ~467.5 Hz pulse frequency between Feb. and June '92 averaged near 10 μHz/day, consistent with the decline observed between each of the three nights in Feb. if frequencies were derived from individual nights. The June result also very nearly lies on the backward extrapolation of the Nov. '92 and Feb. '93 data, which means that the two slopes differ by a factor of two, also indicating erratic spindown behavior.

It is possible that the pulsar is continuously readjusting its moment of inertia, or glitching, so that, much of the time, the spindown is diminished, or even cancelled entirely. If this is the case, then such glitching can not *always* reduce the effective oblateness/moment which causes the precession and GR-driven spindown (of any pulsar implied by the 2.14 ms signal), since this quantity appeared to grow during the Feb. '92 to Feb. '93 interval.

The high pulsar spindown implied by the 2.14 ms signal forces the rotational equilibrium configuration to change by a significant fraction of the implied non-axisymmetric oblateness in one month, and it may be impossible for such a pulsar to adjust sufficiently rapidly through glitching to reduce the oblateness. However, such instabilities obviously do not grow in any other ms pulsars, even those spinning more than 30% faster (Backer et al. 1982, Fruchter et al. 1988), since none of these shows any evidence of the triaxiality associated with the complicated behavior discussed here. However, no other pulsar is only a decade old, and perhaps this one has unique physical conditions which perpetuate the instability, and/or the triaxiality can not grow in other rapidly spinning pulsars for sufficiently small perturbations.

Given that the instability does operate for the implied 2.14 ms pulsar, it may be possible that the "actual" spindown (due to all radiative and wind processes) could be much greater than the mean value of (-)3×10^{-10} Hz/s (possibly as high as that which would be produced by a non-axisymmetric oblateness equal to the ratio of the two periods, $\sim2\times10^{-6}$, or nearly (-)5×10^{-9} Hz/s). The resulting strain parameter at the distance to the Earth would then be four times greater still than the implied strain parameter (Shapiro & Teukolsky 1983) near 10^{-26} (to 4×10^{-26}), and the implied luminosity 16 times greater, near 5×10^{40} ergs/s – over 100 times that of the Crab.

Contributions to the increasing quadrupole moment might also come from sources other than crustal deformities "frozen in" at a time shortly following core collapse (Pines & Shaham 1972a). The one-year steepening of the declines in pulse frequency and modulation period could be caused by progressive realignment of "bumps" on the star to more favorable positions, such as a greater distance from the stellar rotational pole. The observational constraint on such bumps dictates that they can not be close to the rotational equator, otherwise the precession period would cease to decline, and, when they reach the equator, the precession would die off completely. It is possible that the occasions when the 2.14 ms signal is detected, but the precession is not, may correspond to such circumstances.

4.2 Emission Mechanism

The suggested mechanism, for generating the optical luminosity implied by the 2.14 ms signal, is cyclotron radiation by electrons (or positrons) in the pulsar's "outer gaps." These, in turn, depend upon pair production, in these same gaps near the light cylinder, by GeV γ-rays, which are always present in pulsars to some degree, with thermal X-ray photons from the stellar surface (Cheng et al. 1986). Even the soft X-ray flux from the stellar surface due to a thermal temperature as high as $\sim$1.5 keV, almost an order of magnitude higher than most projections (Nomoto & Tsuruta 1986), presents no problem for the current bolometric luminosity limit (Suntzeff et al. 1999, Lucy et al. 1991, Bouchet et al. 1991) for the remnant near 1.25-2.0$\times10^{36}$ ergs/s, and the avalanche started by each pair in the gap can generate as many as 10^4 gamma-rays in order not to strain the observational limits in that band (Kerrick et al. 1992, Ait-Ouamer et al. 1992, Matz et al. 1988).

Assuming that pure magnetic dipole radiation from a 2.14 ms pulsar, with a moment of inertia of 5×10^{44}gm-cm^2, powers a luminosity at the limit quoted above, and relating the implied period derivative to yield an implied strength of the neutron star surface magnetic field by $B = 3.3\times10^{19}(P\frac{\partial P}{\partial t})^{1/2}$, gives an estimate for the field of 1.2-1.5$\times10^9$ gauss (Manchester & Taylor 1977, Lyne & Graham-Smith 1990). The actual field strength can not exceed this estimate by a factor of 10 without making the remnant brighter than is currently observed. For the light cylinder radius of 10 stellar radii, the relativistic "boost" factor (squared) would be $\sim$100 (Cheng et al. 1986), and for a 1.5$\times10^9$ G surface field the cyclotron frequency at the light cylinder would correspond to photons with wavelengths between 750 and 1,500 nm, so far in good agreement with the observations.

The apparent optical luminosity of this object in the 800-900 nm band varied by at least two magnitudes, centered around that of the Crab pulsar (I=21.63 at the LMC with the Galactic extinction removed), although we suspect that, had we continued to observe in that band, fainter detections/limits may have resulted after Sep. '93. Since the pulsar could be expected to be traveling at up to a few hundred km/s through the young, diffuse remnant, in which may have formed a substantial mass of interstellar dust (Ops. cit., & Dwek (1988), Suntzeff et al. (1991)) and/or ions (Op. cit., & Fransson & Kozma 1999), the variability only requires clumping on scales of an astronomical unit. Given a dust cross section of 4,500 cm^2/gm, a density of order 10^{-17}gm cm^{-3}, or nearly an order of magnitude enhancement in the density of dust over the mean density of *all* ejecta within the 2,500 km/s shell after eight years of expansion, would be required to produce a unit of optical depth through one astronomical unit.

In an attempt to obtain more significant results, a broader filter was used following the discovery of the pattern of the 2.14 ms signal in Feb. '93. However the evidence points to the pulsar fading after Sep. '93, at least through Feb. '96. Thus we do not know if the apparent luminosity of the implied pulsar varies intrinsically, or because of changes in opacity, or in the "coherence" of the pulsations. Even accounting for all of the evidence for the 2.14 ms signal, it is still possible that the emission is restricted to the B and I bands, which differ in wavelength by almost exactly a factor of two. This would suggest that cyclotron radiation from a region of relatively homogeneous magnetic field could be responsible for the pulsed optical emission, and if so, it is more probable that such emission could be highly beamed, which would explain some of the variability of the source implied from the 2.14 ms signal.

4.3 Pulsar Formation

Second only to the recent detection of a 62 Hz pulsar with a spindown age comparable to its 4,000-year old remnant, N157B (Gotthelf & Wang 1996, Wang & Gotthelf 1998), SN1987A has provided the best evidence so far that some weak-field ms pulsars may be born with their very rapid spin in SNII (Brecher & Chanmugam 1983, Michel 1987, Chen 1993). Due to the blue giant nature of, the extreme mixing of the elements within (Fransson et al. 1989), and the unusual ring-like structures surrounding the progenitor (Wampler et al. 1990, Jakobsen et al. 1991, Crotts & Heathcote 1991, Podsiadlowski et al. 1991, Burrows et al. 1995, Panagia et al. 1996), it is not unlikely that the explosion of Sk - 69°202 resulted from the coalescence of two stellar cores in a close binary system (Chen & Colgate 1994). Although many other binary scenarios have been put forward (Hillebrandt & Meyer 1989, Podsiadlowski & Joss 1989, Chevalier & Soker 1989), it may be that only the core-merger can explain all the anomalies. Collisions between pairs of binary systems, a necessary step for core-collapse in globular clusters, may be the way such clusters produce their over-abundant supply of weak-field ms pulsars (Kulkarni et al. 1990, Chen & Leonard 1993, Chen & Colgate 1994), as well as the blue stars now found to be commonplace in the cores (Cool et al. 1997). In fact, a recent review of globular clusters concluded that, in addition to ms pulsar formation by post collision accretion, from companions and disruption disks, onto neutron stars, there had to be a third way to form the ms pulsars found in globulars (Bailyn 1995). It is possible that this third mechanism – mergers of white dwarfs – dominates the first two mechanisms. If this is indeed the case, then it is no surprise that the fastest known ms pulsar in a globular also has a period of 2.1 ms (Manchester et al. 1991). Once such pulsars are formed, their later incorporation into accreting binary systems may be the way the low mass X-ray binary systems (LMXB's) are formed, and the LMXB's in globular clusters are related to the weak-field ms pulsars as offspring, rather than as progenitors (Chen et al. 1993). Of all other pulsars, 1821-24, the 3 ms pulsar in the globular cluster, M28 (Lyne et al. 1987), is the most similar to the 2.14 ms signal in pulse profile, high frequency derivative, and position above the "spin-up" line on the $p - \frac{\partial p}{\partial t}$ plane (Chen & Ruderman 1993). However, even though 1821-24 has the largest spindown power of all the known millisecond pulsars, this power still limits its gravitational luminosity to be a thousand times smaller than that implied for SN1987A by the 2.14 ms signal. Moreover, 1821-24 is likely to be sufficiently old (particularly if it was born with a 2 ms spin period) that the asymmetry or thermal flow necessary for gravitational radiation no longer exists.

As the possible glitching does not always seem to be (directly or promptly) reducing the implied non-axisymmetric oblateness of 5×10^{-7}, forces other than the material strength in the crust could be contributing. One possibility might be the generation of the magnetic field from within the star by thermal processes, which could have such side effects (Blandford et al. 1983). Another, perhaps related possibility, would be the pressure due to a "buried" magnetic field, several times 10^{14} G, resident in the crust. The "burial" of the field might take place when a prompt reverse shock, which only occurs in SNII of the smaller, blue giant progenitors, arrives back at the neutron star a few hours after the core-collapse (Woosley & Chevalier 1989). The extra material accreted would also leave the neutron star a few tenths of a solar mass heavier, and the buried field could persist as long as the currents, from which it arises, persist, possibly several years or longer.

However, the buried field/reverse shock mechanism may have problems overcoming the radiation pressure from the decay of the newly-formed 0.075 $M_\odot$ of ^{56}Ni, and/or extreme angular momentum of the progenitor of SN1987A (unless core coalescence didn't happen), and it is not necessary to explain the weak field strengths in the core-merger scenario, which the typically low fields (relative to the reciprocal of the surface area) of the two white dwarf cores already guarantee, provided neither core has burned to iron, as seems likely. Nevertheless, there is slight evidence that the weaker field neutron stars are more massive than those with strong fields (Middleditch & Nelson 1976, Middleditch 1983, Hutchings et al. 1977, Hutchings et al. 1985, Taylor & Weisberg 1989, Thorsett et al. 1993, however, Stairs et al. 1998) and perhaps some features of both pictures could be correct.

Still another possibility is that the non-axisymmetric contribution to the oblateness is somehow a result of the core merger process suspected to have produced SN1987A. If this is the case, then the pulsar remnants of the more "ordinary" core collapse SNe would not be expected to show such a large non-axisymmetric component of oblateness. Unfortunately, it may take another 300 years to confirm or refute this hypothesis, as pulsar remnants will have to be identified from two *more* nearby SNe whose light has not yet even reached the Earth. However, there have already been indications of an energetic central source in SN1993J (Bartel et al. 1999a,b). Since the progenitor is believed to have been a red giant star in a binary, but with an unmerged core which *would* have had time to progress to the Fe catastrophe, this is consistent with the arguments given above regarding the relationship of weak-field, fast pulsars with core-mergers. Moreover, such a pulsar would be expected to be as bright as 28.5 magnitudes, consistent with the occasional 21 magnitudes of the 2.14 ms signal apparently associated with SN1987A, and would be within reach of Keck using observing equipment cited in this work (Shearer et al. 1997, 1998).

The newly-discovered X-ray point source near the expansion center of Cas A may help shed some light on these questions, once a spin period is identified (Tananbaum et al. 1999, Aschenbach 1999). However, it may be difficult to establish whether this SNa was was a result of the core-merger process.

4.4 Future Prospects

At some time in the future the compact remnant of SN1987A may be detectable as a radio ms pulsar (however, see Weatherall 1994). At some more distant future time, probably not in our lifetimes, the compact remnant's soft X-ray flux will wane as it cools so that it can not sustain optical and near-infrared pulses. Since the spindown implied by the 2.14 ms signal seems to be (mostly) diminishing over time since early 1993, its gravitational signal could remain forever beyond the reach of projected detectors such as LIGO. However, there is hope that, with new designs (Sun et al. 1996), LIGO could detect the rapid signature (likely at 1.07 ms). Meanwhile, we would like to determine the spectrum of any optical pulsations in order to better understand the nature of the emission mechanism and the distribution and dissipation of interstellar dust within the remnant. If somehow, the proper motion of the pulsar remnant of SN1987A can be determined, then it may be useful in determining the mechanism by which SNII actually managed to explode (Herant et al. 1994, Hansen & Phinney 1997, Fryer et al. 1998, Cordes & Chernoff 1998). The likely extreme angular momentum of the progenitor may also imply the formation of planets (Wolszczan & Frail 1992, Chen 1993), on whose existence, due to the lack of rotational stability implied by the 2.14 ms signal, we can presently only speculate.

5 Conclusion

We have presented evidence of a 2.14-ms pulsar in the remnant of Supernova 1987A collected with a variety of telescopes, instruments, and data-recording systems over a 4-year timespan. As of Feb. '93, the statistical probability of the signal being due to noise was very low, near 1 part in 10^6. And, taken at face value, and there is no reason to do otherwise, the first few following observations from Tasmania and HST/HSP confirmed the reality of the signal to approximately the same high degree of confidence. The fading of the signal subsequent to Sep. '93, before it could be observed by the large telescopes with more open bandpasses, would be a cause for considerable concern if the results from the other telescopes hadn't also fallen off during the same interval. In addition, the broadband magnitudes of the detections from Tasmania and the HST/HSP are consistent with the narrowband magnitudes of the detections on the large telescopes during the same epoch.

While the 2.14 ms signal implies an unique, optical ms pulsar, and displays a variety of complicated behaviors, such as changes in the pulse shape and modulation consistent with gravitationally dominated spindown and precession, these behaviors may be compatible with that of a newborn pulsar, which might not be able to adjust its equilibrium configuration as rapidly as its high rates of spin and spindown change it.

Thus, given the large amount of data showing evidence suggesting the existence of such a pulsar, and the large investment of telescope and other resources made by the astronomical community in collecting such data, it is our duty to report this 2.14 ms signal as a very promising candidate for the pulsar remnant of SN1987A, and to make this vast amount of data generally available for continued analysis.[18] Though it may remain forever impossible to *rule out* a pulsar remnant for SN1987A, it is possible, and, as we argue above, very *likely*, that the remnant has already been discovered.

[18] The data taken over the interval starting during Feb. '92 and ending during Feb. '96 will be available upon request via anonymous ftp to wwwc3.lanl.gov (204.121.6.32), in addition to xeroxed observing logs and a "readme" file.

A The Lack of Any "Normal" Pulsar in SN1987A

A.1 The Nature of Pulsar Spindown

A number of distinct physical mechanisms cause the braking of a pulsar's spin to be a power law function of frequency,

$$\frac{\partial f}{\partial t} = -\alpha f^n, \tag{A.1}$$

where α is a constant, f is the pulsar frequency, and $\frac{\partial f}{\partial t}$ is its time rate of change (Manchester & Taylor 1977, Lyne & Graham-Smith 1990). The rotational energy, $2\pi^2 I f^2$, where I is the moment of inertia of the pulsar, is diminished via radiation or transferral to the interstellar medium, thus $\frac{\partial f}{\partial t}$ is typically negative. For pure magnetic dipole radiation, $n = 3$, whereas for pure wind-type processes, $n = 1$. For pure gravitational quadrupole radiation, a process which will only occur if the spinning body has a non-vanishing quadrupole moment, i.e., some degree of non-axisymmetry, $n = 5$. If, for any particular epoch, a pulsar's frequency, f, and its first and second time derivatives, $\frac{\partial f}{\partial t}$ and $\frac{\partial^2 f}{\partial t^2}$ are known, and the pulsar has no other processes, such as glitching, which abruptly changes these parameters, then n can be calculated by:

$$n = \frac{f \, \frac{\partial^2 f}{\partial t^2}}{(\frac{\partial f}{\partial t})^2}. \tag{A.2}$$

For the Crab pulsar, $n = 2.5$, implying (in spite of its glitching) a spindown dominated by magnetic dipole radiation.

For observations of such young pulsars with large spindowns, spanning a time range, T, amounting to more than a fraction of a day, the absolute value of the term, $\frac{\partial f}{\partial t} \times T^2$, would be expected to exceed unity, which makes its detection by straightforward Fourier transformation a problem (at 1.35 some 10% of the Fourier power, due to the pulsar signal, would be lost, and the loss increases *quadratically* as $\frac{\partial f}{\partial t} \times T^2$ increases). For example, for one day of data from the Crab pulsar, which has a frequency derivative of -3.8×10^{-10} Hz/s, this quantity would be -2.8.

For a pulsar with a given dipole magnetic field strength, or gravitational quadrupole moment, Eqn. A.1 implies that the faster the pulsar is spinning, the greater the spindown. Also, by integrating Eqn. A.1 there are other motivations to expect that $\frac{\partial f}{\partial t}$ is strictly proportional to the pulsar's spin frequency, f (Middleditch & Kristian 1984). This is also the effect produced on a pulsar signature if it were placed in a frame of constant acceleration.

In any case, it is also a simple matter to introduce, to any time series, a time lag which increases quadratically with barycentric time, in order to correct for a particular negative $\frac{\partial f}{\partial t}$ at a given frequency, f_o. For such a "stretch," or deceleration ($a = c\frac{\partial f}{\partial t}(f_o)/f_o$) of the time series, the Doppler formula guarantees that the frequency derivative at another frequency, f, scales proportionately, or

$$\frac{\partial f}{\partial t}(f) = \frac{\partial f}{\partial t}(f_o)\ f/f_o \ = \ af/c. \tag{A.3}$$

A.2 A Deep $\mathbf{f} - \frac{\partial \mathbf{f}}{\partial \mathbf{t}}$ *Search*

Thus, aside from the normal, night-by-night Fourier searches, done on all of the data listed in Tables C.1-C.2, which utilized a standard algorithm to search the Fourier spectrum for significant single frequencies[19] and trains of harmonics (Middleditch et al. 1992), a further analysis was done which compensated for $\frac{\partial f}{\partial t}$ as described above. This larger analysis utilized billion point fast Fourier transform (FFT) algorithms, performed on supercomputers at Los Alamos National Laboratory, on the three nights of data taken at the CTIO 4-m telescope during late Dec. '93 – the most sensitive data taken to date (see Tables C.1 & C.3). The details follow closely to similar searches done previously (Middleditch & Kristian 1984) (see Table A.1). First, seven a's (the first a is 0) were applied to the original data sequence, the results of which were then each Fourier transformed and searched for significant peaks and trains of harmonics. The spacing between the a's was set so that any pulsar spinning at up to 30 Hz with a $\frac{\partial f}{\partial t}$ up to 16% greater than that of the Crab pulsar ($-4.463 \times 10^{-10} Hz/s$) would have suffered less than 10% loss of power in the worst case mismatch of $\frac{\partial f}{\partial t}$(used) to $\frac{\partial f}{\partial t}$(actual). These runs were also valid for frequencies above 30 Hz (recall that the $\frac{\partial f}{\partial t}$'s scale strictly linearly with frequency, e.g., the $\frac{\partial f}{\partial t}$ at 60 Hz is twice that at 30 Hz, etc.), except that the $\frac{\partial f}{\partial t}$'s (when scaled up for the higher frequencies) were too sparsely spaced to avoid greater losses of signal-to-noise ratio. So three more runs were made with a's at steps 1/2, 3/2, and 5/2, which fell midway between the first previous 4 a's at steps 0, 1, 2 and 3. This extended the validity of the search (in terms of a similar recovery of Fourier power) to twice the frequency (in this case, 60 Hz) up to the same maximum $\frac{\partial f}{\partial t}$ (to $3\frac{1}{4}$ of the previous steps). The procedure continued for four more octaves in frequency, so that the last three runs made a $\frac{\partial f}{\partial t}$ range valid for frequencies up to 960 Hz (see Table A.1).

Because the $\frac{\partial f}{\partial t}$ spacing increases linearly with frequency above the lower oc-

[19] The 7σ sensitivities can be determined by subtracting 1.36 magnitudes from those given in these tables, which gives a typical value of 22.6 for the LCO runs in the 500-900 nm band

tave value, pulsars with frequencies which fell between the octave frequencies, with $\frac{\partial f}{\partial t}$'s in the upper 1/2 range of the steps at the lower octave frequencies, suffer more than 10% loss of power in the worst case mismatch. However, for a pulsar with a frequency derivative which does not exceed that of the Crab's, the backward extrapolation of the search at the higher octave frequency ensures that no more than 10% power is lost for frequencies between 1.67 and 2.0 of the lower octave frequency. Pulsars with frequencies in the remainder of the range and a Crab-like derivative lose 10-25% of maximum power in the worst case mismatch of $\frac{\partial f}{\partial t}$ (the maximum loss occurs for frequencies 57% higher than the lower octave frequency).

The search of the CTIO data would detect any "normal" (constant pulse profile and non-sideband modulated) pulsar with frequency between 25 and 960 Hz, and a Crab-like frequency derivative down to a luminosity corresponding to apparent magnitude 24 for the 500-900 nm band (see Tables A.1 and C.1). Although high $\frac{\partial f}{\partial t}$'s are not covered for the frequencies much lower than 15 Hz, the search would have detected PSR0540-69 with 50% of the $\frac{\partial f}{\partial t}$ range to spare.

The most significant candidate corresponded to a signal of 24.4 magnitudes with about 24-22.5 times mean power in a 238.8 Hz fundamental, but only 1-3 times mean power in the 2nd harmonic, and a frequency derivative of -1×10^{-10} Hz/s. Another candidate, near 892.1 Hz, appeared in the run where $\frac{\partial f}{\partial t} = 0$, with a slightly negative frequency derivative of -2.3×10^{-11} Hz/s, and corresponded to magnitude 24.3. However, it's significance (and its modest 2nd harmonic) diminished when the 100 μs resolution data were checked.

The limit of 24th magnitude for a 50% duty cycle sinusoidal pulse profile is more sensitive still than the most sensitive published observations to date (Manchester & Peterson 1996). The power which persisted over the three nights from the 2nd harmonic of the 2.14 ms signal (see below) was only about two thirds that needed to trigger harmonic searching (Middleditch et al. 1992), and the magnitudes for the signals seen were 24.77, 24.44 and 24.78 (Table C.3). Figure A.1 plots the range for $\frac{\partial f}{\partial t}$'s from each sequence of runs (see Table 1), in addition to the worst case % power recovery (snr $\sim$ $\sqrt{power}$, loses 5% when power loses 10%) as each sequence is extrapolated backward to the 1/2 the f_{max} and forward to twice the f_{max}.

Table A.1
Deep CTIO 4-m Search Parameters, 28-30Dec93 UT

Step	f_{max} [a] (Hz)	$\frac{\partial f}{\partial t}(f_{max}) \times T^2$ [b]	$\frac{\partial f}{\partial t}(f_{max})$ [c] (Hz/s)	-a [d] (cm/s/s)
0	30.	0.0	0.	0.
1	30.	2.7	-6.866×10^{-11}	0.0686
2	30.	5.4	-1.374×10^{-10}	0.1372
3	30.	8.1	-2.060×10^{-10}	0.2058
4	30.	10.8	-2.748×10^{-10}	0.2744
5	30.	13.5	-3.433×10^{-10}	0.3431
6	30.	16.2	-4.120×10^{-10} [e]	0.4117

Successively finer steps in $\frac{\partial f}{\partial t}$

f_{max} [a] (Hz)	$\frac{\partial f}{\partial t}(f_{max})T^2$ [b]	$\frac{\partial f}{\partial t}(f_{max})$ [c] (Hz/s)	-1000a (cm/s/s)
60,120,240,480,960	2.7	$-6.866e-11$	34.31, 17.15, 8.577, 4.288, 2.144
60,120,240,480,960	8.1	$-2.060e-10$	102.9, 51.46, 25.73, 12.86, 6.432
60,120,240,480,960	13.5	$-3.433e-10$ [f]	171.5, 85.77, 42.88, 21.44, 10.72

[a] This is the maximum frequency which suffers less than 10% loss of power in the worst case mismatch to $\frac{\partial f}{\partial t}$.

[b] Steps of 2.7 in this parameter guarantee 10% loss of power for the worst case mismatch of $\frac{\partial f}{\partial t}$. T here is the time span of the data, or about 1.98×10^5 s.

[c] These $\frac{\partial f}{\partial t}$'s are valid only when the frequency being searched is f_{max}. For other frequencies, $\frac{\partial f}{\partial t}$'s scale proportionately, e.g., at a frequency of $2 \times f_{max}$ the appropriate $\frac{\partial f}{\partial t}$ is twice as big.

[d] This is the acceleration which describes the time stretch, in $a = c\ \frac{\partial f}{\partial t}(f_o)/f_o$.

[e] The search recovers more than 90% Fourier power until $\frac{\partial f}{\partial t}$ exceeds the next 1/2 step, which, in this case, corresponds to -4.463×10^{-10} Hz/s.

[f] Because of the cruder steps which occurred for the sequence of $\frac{\partial f}{\partial t}$'s at the previous frequencies (30 for 60, 60 for 120, etc.), all of these searches are valid for the range from 0 to $(\frac{13/4}{5/2} = 1.3) \times -3.433 \times 10^{-10} \ = \ -4.463 \times 10^{-10}$Hz/s.

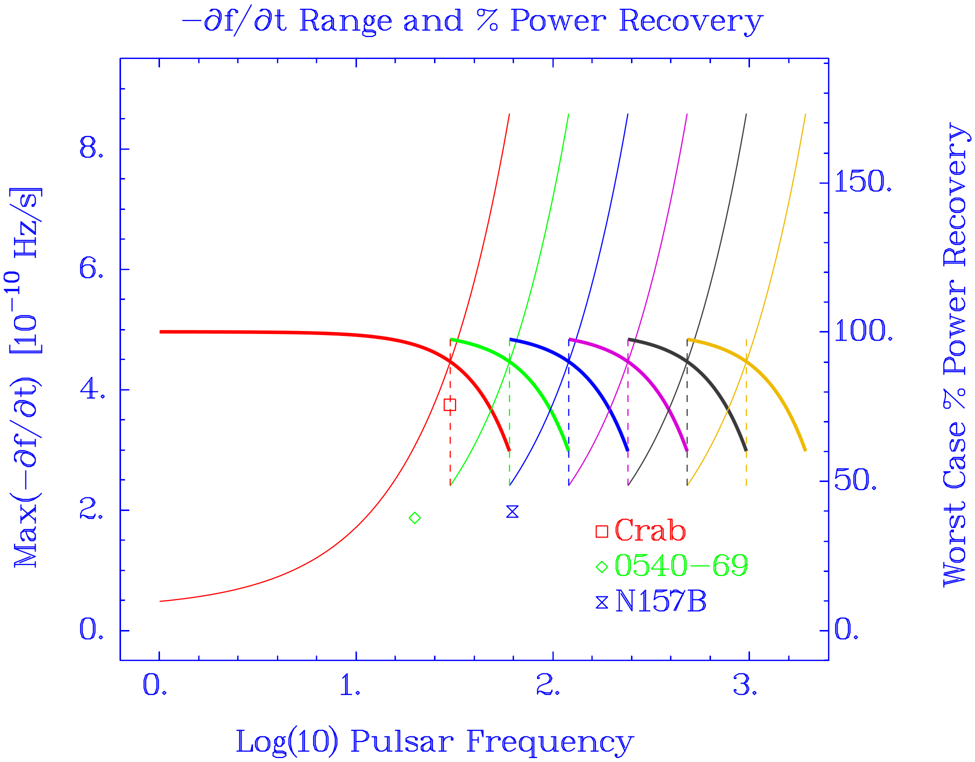

Fig. A.1. (Thin lines, monotonically increasing) The maximum $\frac{\partial f}{\partial t}$ ranges (labeled on the left ordinate), covered as a function of pulsar frequency, by calculations with $f_{max} = 30$, 60, 120, 240, 480, & 960 Hz respectively (dashed lines), from left to right, with the domain of each line (except for the leftmost) extending from 1/2 f_{max} to 2 f_{max}. (Thick lines, monotonically decreasing) The worst case % power recoveries (labeled on the right ordinate) for the same frequency domains.

B More Detections of the 21.4 ms Signature

B.1 November 1992

For this data, a targeted search was made which covered frequencies down to 467.488 Hz and in which the Fourier power spectrum near the first two harmonics of 467.5 Hz (resulting from the long transform of data from all three nights) was contoured in (f, $\frac{\partial f}{\partial t}$) space. This space was searched for peaks with f's and $\frac{\partial f}{\partial t}$'s (roughly consistent with the extrapolation to the f's from Feb. '92) in 1:2 ratios, with null results. The lower limit frequency for the search was determined by extrapolation from the previous Feb. using negative frequency derivatives down to -2.1$\times10^{-10}$ Hz/s, i.e., the next highest candidate frequency derivatives listed as the 2nd and last entries to Table 1.

The search described above failed to detect the 2.14 ms candidate primarily because the range of $\frac{\partial f}{\partial t}$ used in the extrapolation from Feb. '92 was not sufficiently large. However, once the $\sim$467.5 Hz frequency was known exactly during Feb. '93, the frequency *interpolated* between the Feb.'92 and '93 data was lower, and a peak was found in the Fourier spectrum of the Nov. 6th data (the best night of the three), with $\sim$13 times mean power, occurring at 467.489354 Hz, in addition to another very nearby peak with half the power.[20] Neither of these peaks had significant power at their respective higher harmonic frequencies. And close as they were, their frequencies were still far from the 467.4866 Hz frequency interpolated between 467.4934 Hz in Feb. '92, and 467.4843 Hz in Feb. '93.

However, although the sum spectrum of the first and 2nd harmonics of the Nov. '92 data showed little near the interpolated frequency, the sum spectra of the 2nd and 3rd harmonics[21] showed unusual peaks for the nights of Nov. 6 and Nov. 8 modulo 467.4875 Hz – nearly three times closer to the linearly interpolated frequency. These were the highest in all three sums over a range of nearly 6 mHz for the Nov. 8 result, and more for Nov. 6.

We postulated that the high Fourier peak in the Nov. 6 data at 467.489354 Hz could be a 2nd upper sidelobe of an $\sim$1,000 s modulation of the 2.14 ms periodicity, similar to the pattern observed in Feb. '93, with a fundamental frequency near, but little or no power at, 467.4875 Hz. The frequency of this postulated 2nd upper sidelobe, when combined with the frequency of the fundamental at 467.4875 Hz (as implied by the frequencies of the actual power peaks found at the 2nd and 3rd harmonics), suggested that the modulation period was near 1,100 s during Nov. '92. This, however, would also imply that the modulation period was changing rapidly in a fashion similar to the 467.5 Hz pulse repetition frequency, a conclusion we had already considered from the re-examination of the Feb. '92 data. When we tested the modulation spectra of this data, phase modulation of *both* the 2nd and 3rd harmonics with the $\sim$1,100 s period was evident in the (more significant) results of 6 Nov. '92, lending credibility to the association of the 1,100 s modulation period with the Nov. '92 data.

[20] The 1.5 Fourier spacing offset from the higher peak indicated that the sinc function lobes of the higher peak had added "in phase" with noise already present, as was verified by the reduction in power in the smaller peak when the main peak was removed from the continuous interpolation – see Middleditch et al. (1981).
[21] There are *two* possible relative phases for the coherent sum of the second and third harmonics – the phase, $\phi(3f)$, in the generalization of Eqn. 1, is ambiguous by 180° relative to $\phi(2f)$.

B.2 Observations from HST/HSP and Tasmania, 1993

By the time the pattern of the 2.14 ms signal was beginning to be discerned, the regular '92/'93 observing season was over. In order to continue observations during an interval in which the signal seemed reasonably consistent, observations had to be made from farther south. Thus the search continued with the 1-m telescope of the University of Tasmania, which was sufficiently far south to allow observations of SN1987A from under the pole (and through at most 2.7 airmasses).

B.2.1 May 16, 1993

For the initial observation made from Tasmania on May 16, 1993 UT, a peak at 467.481992 (5) Hz was the highest of three sum spectra (1+2, 2+3 & 2-3), which ranged over a full 23 mHz modulo $\sim$467.5 Hz. The pulse frequency was within 100 μHz of an extrapolation from the 467.4843 Hz signal seen between 3 and 12 Feb. '93, using the mean loss from Feb. '92 of 25.28 μHz/day. The "standstill" of the 467.4843 Hz signal observed in that epoch (see §§3.3.1 and 4.1.2), and the very steep mean decline in frequency observed since Nov. '92 would make the extrapolation uncertain by 1 mHz, but examination of HST/HSP data from 6 Mar. '93 (available a year later), with a plausible detection between these frequencies at 467.48406 Hz (see below), would reduce this uncertainty.

As SN1987A was observed almost directly under the pole using a smaller aperture, the magnitude of the pulsation is probably a bit more uncertain than the others. The pulse profile was dominated by 2nd harmonic structure with broader (and flat-topped or square-looking) pulses than typical, but with a similar mean separation of 0.55 cycles.

The modulation spectra of the dominant 2nd harmonic component of this result showed strong phase modulation with a period of 1009 $\pm$17 s – the largest peak for at least $\pm$35 mHz in either modulation spectrum. The peak corresponded to a phase modulation with an amplitude of about one radian, sufficient to explain the broad, flat-topped appearance of the two pulses. To test whether the sideband peaks near the 2nd harmonic were an indication of an actual toa modulation, the data were folded with the implied modulation of the second harmonic included in the ephemeris. If the sideband peaks were due to just "fluff" near, but unrelated to, the 2nd harmonic, the two peaks in the pulse profile would contain more counts, owing to the modulation power near the 2nd harmonic being incorporated, but would not necessarily sharpen – the expected result if the modulation also affected the higher harmonics in a similar way, with the amplitude of the phase effect proportional to the harmonic number (see also §B.3.2).

When the data were actually folded while incorporating the implied phase modulation, both the main and interpulse sharpened, *and* both moved to the left of the center of the "blurred" peaks (see Fig. B.1), consistent with the actual initial phase measured for the ~1,000 s phase modulation. Both of these results support the contention that the sideband power is associated with a real modulation of the 2.14 ms signal.

Simulations were performed to test the validity of this conclusion. First, ten peaks with about the same level of power as occurred in the 2nd harmonic of the May 16th run (5.9 times mean) were selected, again near the 934.964 Hz 2nd harmonic frequency, from a run whose data sampling rates were corrected to the solar system barycenter. The data were then folded at half the frequencies of these peaks to generate "baseline" pulse profiles. Phase modulation peaks for these power peaks were then identified (in the corresponding phase modulation spectra – see §3.1) which had about as much power as observed for the phase modulation of the May 16 data (6.8). The modulations were then incorporated in the generation of another time series, also corrected to the solar system barycenter, for each of the ten original peaks. These were then Fourier transformed in order to accurately measure the powers in the new 2nd harmonic peaks (and exact frequencies – some shift usually occurs, depending on the beginning and end phases of the modulation) which could then be compared to the sums of the power in the old 2nd harmonic and modulation peaks.

In order to determine what amplitude of phase modulation, z_m, to use, it was assumed that the central power scales as $J_0^2(z) \sim 1 - z^2/2$, and the total phase modulation sideband power scales as $2J_1^2(z) \sim z^2/2$, i.e., it was assumed that z_m was not significantly greater than 1. Thus,

$$z_m = \sqrt{\frac{2P_1}{(P_0 + P_1)}}, \tag{B.1}$$

where P_0 is the initial power in the 2nd harmonic "central" peak, and P_1 is the power in the phase modulation peak. In addition, the data were folded with the phase modulation incorporated at the ten new fundamental frequencies (half the new 2nd harmonic frequencies) and the pulse profiles were examined and their χ^2's noted. This procedure was repeated for the actual signal in order to make a blind test (i.e., to avoid non-identical optimization). On the average, the power expected in the new 2nd harmonic is the sum of the power from the old 2nd harmonic and that in the sideband modulation power (§§B.3.1-B.3.2 will present three apparent exceptions to this rule, all suspected occurrences of the 2.14 ms signal).

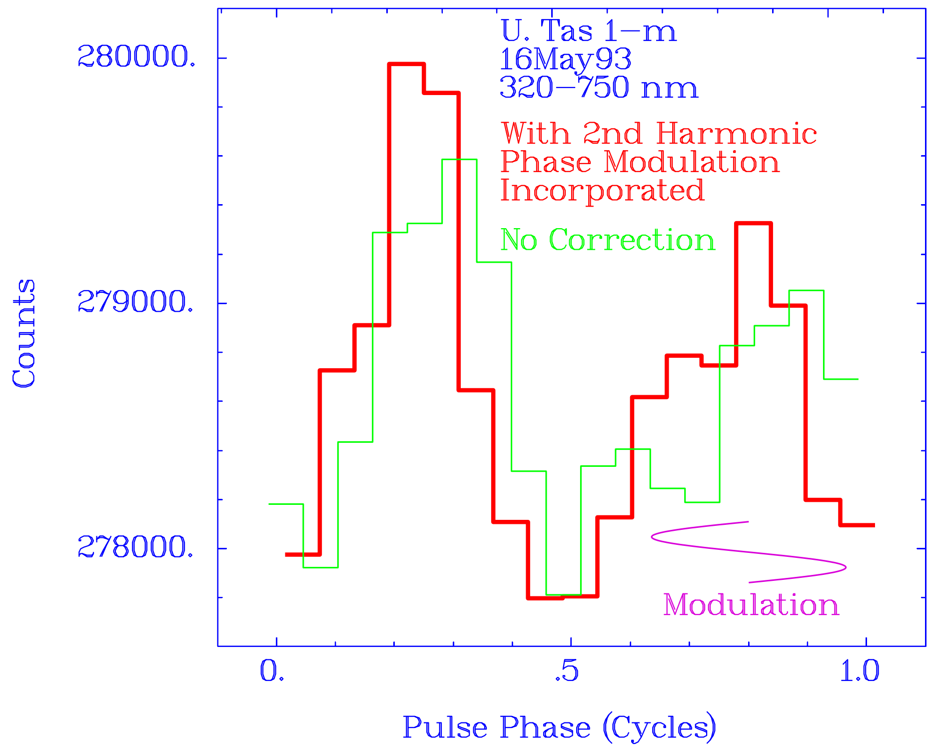

Fig. B.1. The pulse profiles of the 2.14 ms signal found in the data from May 16, '93. (Light profile, displaced to the right) With no correction from the implied 2nd harmonic phase modulation, and (dark profile, displaced to the left) with the correction included.

The result shown in Fig. B.1 is not remarkable on the basis of increase of χ^2 or recovery of expected power from incorporating the modulation (-0.705 – this value is not significantly negative as was that achieved for Feb. 7, '96, possibly because the *2nd* harmonic was demodulated in this example, rather than the fundamental – see §B.3.2). However, it is remarkable in that the post-demodulation pulse profile shows more, and the original pulse profile shows less sharp structure than at least seven of the ten pairs of "comparison" pulse profiles with the same amount of power in that harmonic.

The mean spindown of the 2.14 ms signal implied by the 467.481992(5) Hz barycentric frequency of the May 16, '93 detection, for the interval beginning at the latest previous observation on 12 Feb. '93, is about 24.7 μHz/day, only slightly less than the mean of $\sim$25.4 μHz/day implied by the previous '92-'93 data.

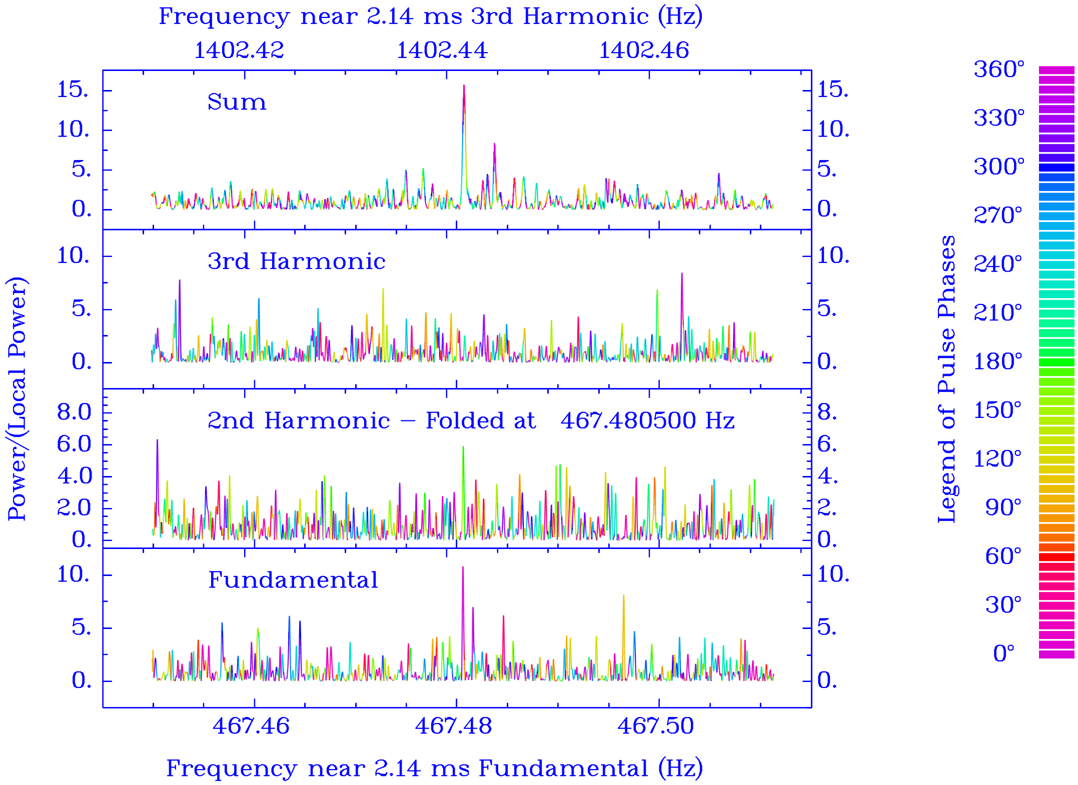

Fig. B.2. (Lower three frames) The Fourier power spectra for frequency regions near 467.4805 Hz and its first two higher harmonics from data taken at the U. of Tasmania 1-m during mid UT July 26, 1993. (Top frame) The sum spectrum of frequencies near the fundamental and 2nd harmonic (see Eqn. 1). The peak in the sum spectrum near 1402.4417/3 = 467.48056 Hz is significant above the five sigma level (probability∼1:6,500,000).

B.2.2 July 26 and August 23, 1993

The July 26 observation, with over ten times mean noise power for a fundamental frequency near 467.48056(1) Hz, and a second harmonic with about half as much power at exactly twice this frequency, produced a strong peak in the sum spectrum (Figure B.2). The seeing deteriorated during the last 20% of the 2.25 hour observation, and the pulsar signal weakened correspondingly. The pulse profile of this signal (Fig.B.3) confirmed the Fourier spectral analysis, indicates a mean magnitude of 21.6 for the 320-750 nm S20 band, and is similar to that of the Feb. '92 observations. Extrapolating 71 days from the May 16th result using a 24.7 μHz/day decline of the frequency predicts a barycentric frequency of 467.48024 Hz, just 320 μHz below the actual barycentric frequency of 467.48056 Hz.

SN1987A was observed again four weeks later on August 23, '93. This run was interrupted after the first hour due to bad seeing and impending cloud, and proceeded for another hour after a half hour gap. Analysis of the better second

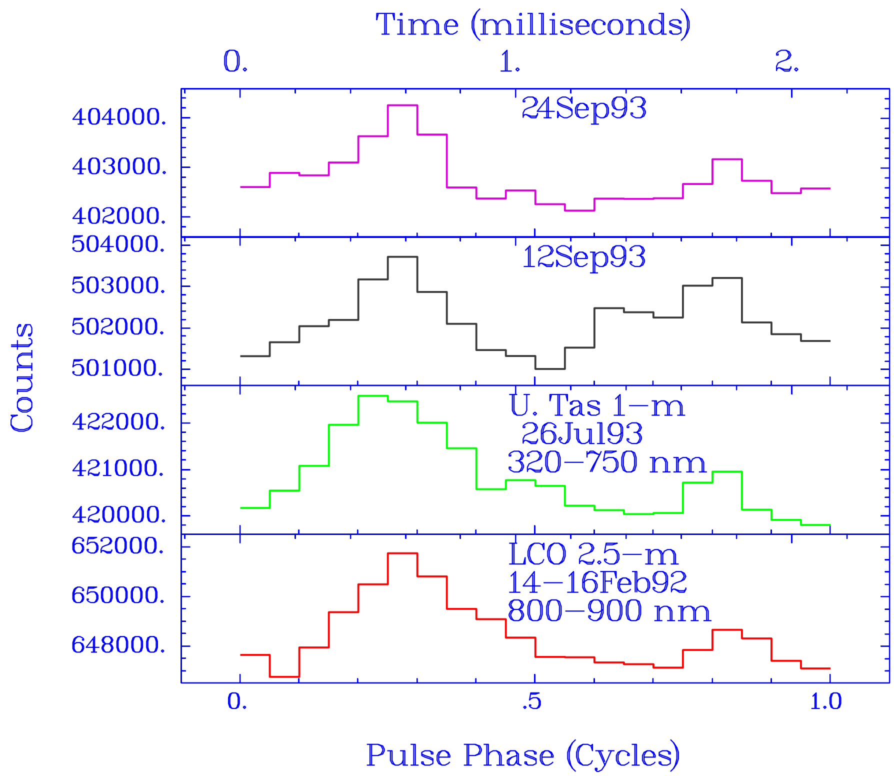

Fig. B.3. The pulse profiles for the 2.14 ms periodicity detected on UT July 26, Sep. 12 and 24 '93 with the 1-m telescope are plotted against the UT Feb. 14-16, '92 detection with the LCO 2.5-m telescope. The relative phases of the profiles have been arbitrarily adjusted.

hour of this observation revealed power in the first through fifth harmonics of the 467.479886(4) Hz frequency. The pulse profile is similar to that of the July 26 data insofar as they are both dominated by a single main pulse (Fig. B.5). Connecting the two sections of data produces a more complicated pattern, with second and third harmonic power at a slightly lower mean frequency (467.478874(4) Hz), an 11-bin pulse profile probability of 2.1×10^{-4}, symptoms of an ambiguous timing noticeable for the 4th harmonic and consistently worse for the 5th harmonic, and a family of upper sidelobes to the 2nd-4th harmonics separated by (1/4000 s) modulo the fundamental frequency. However, the centroids of the 2nd and 5th harmonics (0.67 ± 0.073 and ±0.095, where 0.5 is expected – Middleditch et al. 1992), clearly indicate that the stronger signal lies within the 2nd hour of data (the centroids for harmonics 3 and 4 were also > 0.5).

The pulse profile for this 2nd hour of data is less probable still than that of the July 26 data (2.44×10^{-7}), and the peak in the sum spectrum produced by the 2nd and third harmonics shown in Fig. B.4 is even higher than that shown in Fig. B.2. The structure following the main pulse (Fig. B.5) is significantly

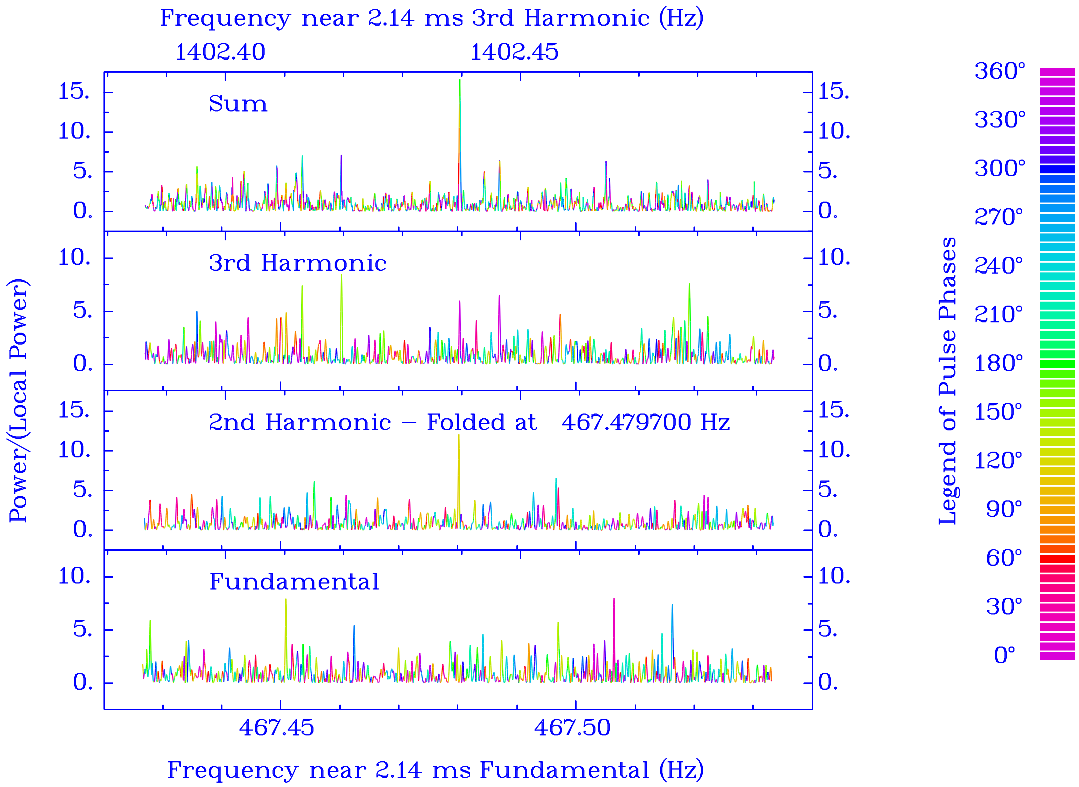

Fig. B.4. (Lower three frames) The Fourier power spectra for frequency regions near the frequency of 467.4797 Hz and its first two higher harmonics (the 2nd near 935 Hz and the third near 1402.5 Hz) from data taken at the U. of Tasmania 1-m during UT August 23, 1993. (Top frame) The sum spectrum of frequencies near the 2nd and 3rd harmonics (see Eqn. 1). The peak in the sum spectrum near 1402.4397/3 = 467.4799 Hz is also significant above the five sigma level (∼1:15,700,000).

less distinct without also folding in the earlier data. The estimated mean magnitude of 20.72 for this result is lower than that of the 26 July result, since about as much signal is accumulated in only one hour instead of two. However, the magnitude for the signal during the two hours of data averages to 21.5.

The difference between the 467.479886(4) Hz barycentric frequency of the August result, and the 467.479923(10) Hz value extrapolated from the July result using the 22.7 μHz/day slope since 12 Feb. '93 (by now much less sensitive to the "standstill"), amounts to only a few percent of the extrapolated 636 μHz decrease (see Fig. 3).

B.2.3 Further Observations, 1993, and Data Issues

SN1987A was observed two more times during August, with no clear signal identified to limits of about 21.5-22.3 magnitudes, mostly because of the lack of power both near the fundamental and second harmonic frequencies, and the lack of any candidate near the "right" place (see Table C.4). Three more observations were made in September, with possible detections on the 12th and 24th (Figs. 3 and B.3, and Table C.4). The data on the 12th showed mostly 2nd harmonic (see below) while the event on the 24th had a peak in the sum spectrum which was a local maximum in the plot analogous to Fig. B.2 (Table C.4, footnote 'h'), which was also very close to the extrapolated frequency.

In addition, the frequency of the Sep. 12 result lies below a straight line fit to the three other non-negative events, which were obtained closest to it in time, by about 66 μHz, or nearly 1.1 Fourier spacings at the frequency of the dominant 2nd harmonic. However, the straight line fit including this point and excluding the 24 Sep. point is nearly as good, with the extrapolation only 85 μHz below its frequency of 467.489142 Hz.

The Fourier parameters of 2nd harmonic peak in power from Sep. 12, '93 indicated a (1.5-2.0 σ) negative $\frac{\partial f}{\partial t}$ (Middleditch et al. 1992), as did the very nearby sidelobes which are also characteristic of a non-zero $\frac{\partial f}{\partial t}$. A look at the $f - \frac{\partial f}{\partial t}$ plane confirmed a negative derivative of -3.45×10^{-8} Hz/s for the second harmonic power, which rose by over 50% to 12 times mean. The pulse profile made without including this derivative had two, nearly equal peaks, spaced nearer to 0.5 than 0.55 cycles, unlike the other pulse profiles dominated by two pulses. When the Sep. 12 data are folded with the implied $\frac{\partial f}{\partial t}$ term included (Figure B3), the pulse profile becomes much more similar to the other profiles in that figure, with a higher sharp main pulse followed 0.55 cycles later by a lower interpulse. The probability of 0.0027 is for no $\frac{\partial f}{\partial t}$, whereas the probability for the 11-bin pulse profile *with* the $\frac{\partial f}{\partial t}$ of -3.45$\times 10^{-8}$ was 9$\times 10^{-4}$, not the minimum for the scan over $\frac{\partial f}{\partial t}$, which was slightly lower at 5$\times 10^{-4}$, and occurred at $\frac{\partial f}{\partial t} = 2.03 \times 10^{-8}$ Hz/s. However, at this point the pulse-interpulse separation was still near 0.50 cycles and the interpulse is nearly as strong as the main pulse (actually stronger counting its 33% greater width).

When -3.45$\times 10^{-8}$ Hz/s is viewed as a quadratic phase error in time over the 2.3 hours, it is a downward-facing parabola which peaks at 106.°4 1.15 hours after starting from 0 (where it arrives again at 2.3 hours). The corresponding rms fluctuation is $\sim$32°.

The two Sep. '93 results were analyzed for modulation periods but no pattern has yet emerged. The lack of strong modulation is consistent with both of these results having sharp pulse structure. In contrast, of the peaks in the sum spectrum for the 26 July '93 result shown in Fig. B.2, the second, fourth and sixth highest are separated from the main peak by exactly +1, -2, and +2 mHz respectively (in the scale of the fundamental frequency, where the major contribution occurs), and result from sidelobes of the 2nd harmonic as well as

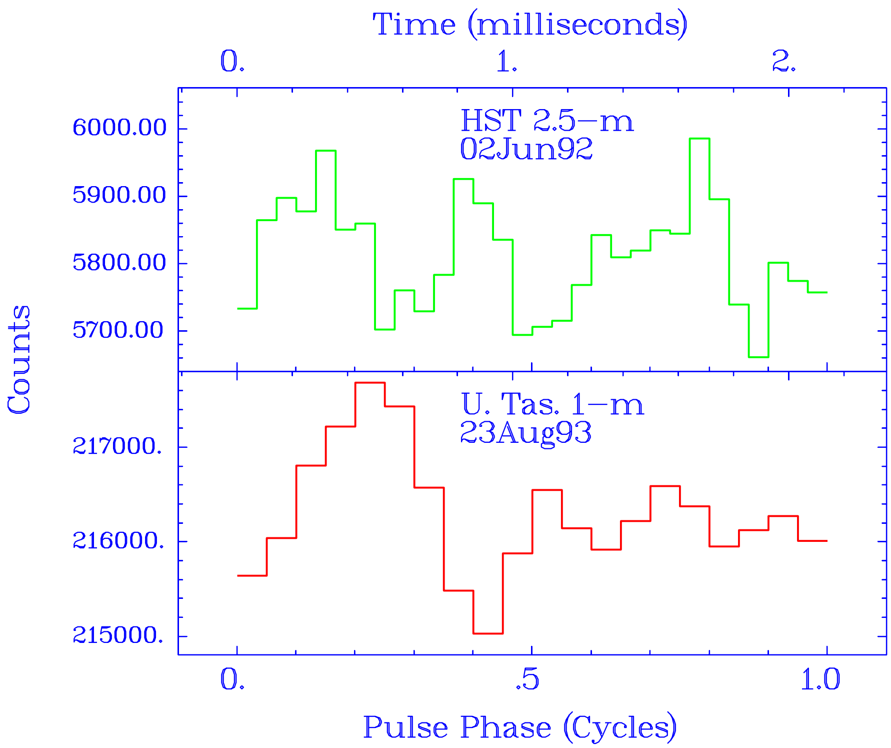

Fig. B.5. The pulse profile for the 2.14 ms periodicity detected on UT August 23, 93 with the 1-m telescope is plotted against the June 2,'92 possible detection with the HST/HSP. The relative phase of the two profiles is arbitrary.

(usually more obvious) sidelobes of the fundamental frequency. As relatively sharp structure persists in the pulse profile (Fig. B.3), it is no surprise that the sideband power near the fundamental and the second harmonic does not project into strong phase modulation. The period of the modulation, as measured from the spacing of peaks at the positions of the first upper, and 2nd and 3rd lower sidelobes (Fig. B.2) is 1001.5 $\pm$10 s.

The very sharp structure in the Aug. 23 result probably indicates that no *strong* phase modulation should exist for that run (and, indeed, none does, even for the very strong 2.14 ms signal seen during the 2nd hour of data).

B.2.4 HST/HSP Observations

A similar analysis of more sensitive data from HST/HSP taken on June 2, '92, with essentially the same bandpass, revealed an unusual event at magnitude 22.7, a barycentric frequency of 467.492310(24) Hz and power in the 2nd-5th harmonics (Fig. B.5). The probability of this pulse profile, when folded into 30 phase bins, is estimated to be 0.001, and the short duration of this run allows only a handful of candidate Fourier elements to search (see Fig. B.6),

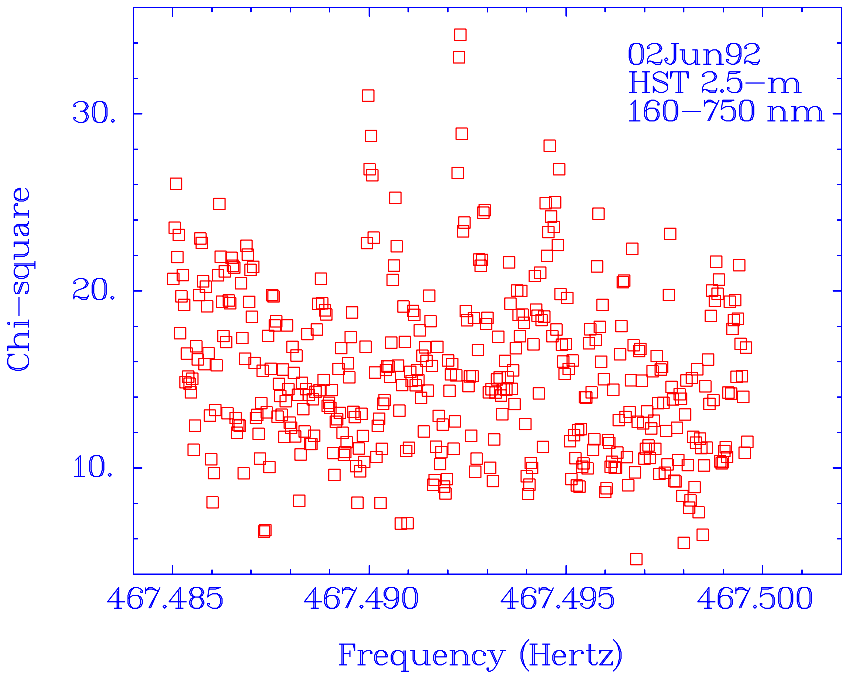

Fig. B.6. The chisquares obtained from folding HST/HSP data taken on June 2, '92 at frequencies near 467.49231 Hz into 30 phase bins are plotted against the folding frequency. The highest point lies very close to an extrapolation and interpolation of the 2.14 ms frequencies, as measured during Feb. '92 and '93. Due to the "centering" of the chi-square scan on this frequency, this value should be reduced by about one unit to render it consistent with the mean losses expected at all other frequencies.

thus the occurrence of such an event is unlikely.

Previous analysis by others of HST/HSP data sets taken in Nov. '92, March '93, and Nov. '93, as well as June '92, quoted limits as faint as 24.5 for all frequencies (Percival et al. 1995). However, these were in error, and the signal shown in Figs. B.5 and B.6, which is sufficiently strong to be unusual only for the restricted frequency range shown, averages near 1 count/s. This corresponds to V=22.7 magnitudes, based on observations of the Crab pulsar, and is consistent with a 7σ limit for a sinewave pulsar at magnitude 22. Also, due to a data artifact with a period of 8.6 ms in the June '92 data set, about 1/4th of the frequency of 467.5 Hz, no such event would have been seriously considered as a candidate, without prior knowledge of the frequency. This artifact actually only modulated the level of the power spectrum sinusoidally by a few percent with a (broad) 116 Hz period, which was easily compensated by the analysis.

In order to verify this detection in a completely fair way, the chi-squares were determined by fine sampling over a large range of frequencies and plotted in Fig. B6. The highest chi-square occurs for a frequency which is within about 300 μHz of any reasonable extrapolation of the Feb. '92 data, or slightly larger than the width of the symbols in the figure. In addition, the two points in Fig. B.6 which are distinct from the highest point and which have the next highest chi-squares, are, to within errors, displaced symmetrically from the main peak frequency by 0.0023 Hz. Another result was obtained in the HSP data taken on March 6, 1993, at a frequency of 468.484065 Hz, again extremely close to any extrapolation from the results from the Feb. '93 observing runs, which preceded it by only three weeks.

Most of the unusual nature of the HST/HSP pulse profile shown in Fig. B.5 comes from very sharp structure, which would not have been noticed in an analysis limited to 11 bins of a cut and weighted pulse profile of data sampled near 5,000 Hz (this would correspond nearly exactly to summing every two HSP data bins to form a time series with a 5019.6 Hz sampling rate). However, as the HSP runs were short (no more than 40 minutes each), and have greater sensitivity, per unit square root of time, than the LCO runs, they represent an unique data sample and, in addition, lend themselves to analyses, such as that shown in Fig. B.6, which would be extremely time-consuming on longer data sets. In addition, given the short duration of the HSP runs, the Fourier spacing was relatively coarse, so that the statistically unusual nature of both of these results was immediately apparent in the very first trial pulse profiles for each of them, made at some reasonable interpolated or extrapolated frequency. The HST/HSP result from March 6th did not have quite such sharp structure as that from June 2nd, as the 11-bin probability was 0.00145, while that for 30 bins was 0.0007.

B.3 Recent Results

The three latest results obtained during Feb. 13 and Oct. 31, '95, and Feb. 7, '96, are worth some detailed examination. All three of these are unusual, for three completely different reasons, in the amount of power recovered from their respective phase demodulations relative to the amounts expected. The first (Feb. 13, '95) shows an unusually high amount of power recovered, possibly due to the presence of the modulation in more than one harmonic (the 2nd and 3rd), while the 2nd (Oct. 31, '95) also shows high power recovery due to an extremely large (but physically still quite reasonable) toa modulation (95.°5 on the 2nd harmonic), while the last (Feb. 7, '96) shows an unusual *deficit* of power due to the extreme sharpness of the demodulated pulse profile.

B.3.1 February 13 and October 31, 1995

The 2.14 ms result from Feb. 13, '95 showed a 2nd harmonic with nearly 11 times mean power very close to the extrapolated frequency from the previous November (the highest such peak in *seven* nights, each with a graph similar to Figs. B.2 & B.4), with a 280.3 s phase modulation, and very little power in the 2.14 ms fundamental or third or higher harmonics. As the 1127(15) s period, implied by an upper sidelobe of the 2.14 ms 3rd harmonic (Table C.5), is nearly exactly four times the 280.3 second modulation, the two periods are harmonically related, and the "true" fundamental period is near 1120 s, a reasonable continuation of the trend shown in Fig. 3.

Incorporating the implied 280 s phase modulation in the pulse profile produced stronger, but only moderately sharp pulse and interpulse. Simulations of 14 other peaks in data, whose sampling rate was also corrected to the solar system barycenter, with frequencies near the 934.936888 Hz 2nd harmonic frequency, show that, although the gain in χ^2 is only slightly better than the mean simulated result (considering that all of these did not have quite as much power as the Feb. 13 2nd harmonic and modulation), the amount of excess power gained by the 2nd harmonic, as compared to the expected gain, was unprecedently large (+2.98) when compared to the results from the simulations (-2.69 to +1.41 – the range only extends to +2.07 by including 39 more simulations). This could be related to the strengthening of both of the two peaks in the profile. Tests of "apparent" phase modulation of the actual 934.936888 Hz signal, with periods of 180 and 463 s and nearly as much power as the 280.3 s modulation, produced unremarkable amounts of relative power recovery (-1.16 and 0.84). Thus the 280.3 s modulation also differs in some way from randomly chosen modulations, possibly because it is present in both the 2nd and 3rd harmonics.

The 2.14 ms result from Oct. 31, '95, is similar to Feb. 13 in its high recovered power, but dissimilar in another way. Although its 2nd harmonic had only modest power (4.72 times mean), it was discovered because its peak in power was broad enough to add to a sharper, and stronger third harmonic peak (which turned out to be not strongly related to the subsequently realized, very highly modulated signal). When its implied phase modulation of 582 s (which can be identified as the second harmonic of an 1164 s modulation), with a power of 6.63, was incorporated in the pulse profile, the resulting power exceeded that expected by 2.59 units – still higher than the relative power recovered in 53 simulations. However, unlike Feb. 13, optimization over the phase demodulation parameters quickly showed that the phase modulation amplitude was nearly 95.°5, much greater than the 62° used in the blind test, and the excess power recovered in the 2nd harmonic rose to +3.95 units (see Table C.3, footnote 's').

The reason for this discrepancy was a 4th harmonic feature in the AM spectrum (with a period of 291 s) with some 5.5 times mean power and nearly the correct phase to correspond to a *2nd order* phase modulation peak,[22] which would scale as $J_2^2(z)$. Occurrences of such a peak, with such good phase agreement, are extremely rare, less than one chance in a thousand, and simulations, including nine specifically designed to match the powers in the central and modulation peaks, verify this result. The corresponding gain in the significance of the demodulated pulse profile, from 4.72 times mean power to the equivalent of a 5σ event ($Prob = 6 \times 10^{-7}$), is also remarkable. Again, tests of "apparent" phase modulation of the actual 934.92767 Hz signal, with periods of 167 and 228 s, produced unremarkable amounts of relative power recovery (-0.58 and -1.59). Thus the 582 s modulation of the Oct. 31, '95 result also differs from randomly chosen modulations, this time, presumably, because of a large 2nd order phase modulation contribution. This 95.°5 phase modulation on the *2nd harmonic* of the ~467.5 Hz signal, which would be *impossible* to produce via precession for the ~467.5 Hz *fundamental* (Nelson et al. 1990), corresponds to only 47.°75 there, which is a perfectly reasonable value for precession, and less extreme than the ~60° amplitudes observed in the May 16, '93 and Feb. 7, '96 data (see below).

The Feb. 13, '95 result showed only near mean power, and a less ideal phase, at its 2nd order modulation frequency (1/(140.15 s)), consistent with the optimum degree of modulation not increasing substantially over that chosen for the "blind" test (Eqn. B.1) as it did for the Oct. 31, '95 result.

B.3.2 February 7, 1996

This result occurred during the first 2 hr and 18 min of nearly 8 hours of data, prior to and during moonrise, when the background was low and the seeing was superior to that which occurred for the remainder of the run.

The sum spectrum for this segment showed a peak at 467.46173 Hz, with symmetric sidelobes corresponding to a 2,500 modulation, which also appeared in the phase spectrum of the ~467.5 Hz second harmonic as a broad peak with over 7 times mean power, together with another, equally broad ~700 s modulation. However, the highest such peak, in the FM spectrum of the dominant ~467.5 Hz *fundamental,* with 7 times mean power, had 11.3 times mean power resulting from nearly 29 cycles of a 288.5±1.1 s period with a marginally significant (2σ) 67.5° quadratic drift of phase (or a $\frac{\partial f}{\partial t}$ of 2.2×10^{-8}

[22] Following Eqn. 4, this would be twice the phase of the 1st order phase modulation, -180°, i.e., $2 \times (-145.°6 \pm 15.°7) - 180° \;=\; -111.°2 \pm 31.°4$, vs $-135.°5 \pm 17.°4$ (see Table C.5). Ordinarily, a harmonic this high in the amplitude spectrum, in the absence of other harmonics as, e.g., occurred here, or in Fig. 5, would not have been considered.

Hz/s), possibly indicating limited coherence.

The 288.5 s period was within 1% of the 4th harmonic of the previously detected modulation period of 1,164 s on Oct. 31, '95 (§B.3.1 and Table C.5, and, if associated with that period, implies no increase over the more than 3 month interval between the two observations. The difference between the frequencies of the two observations gives a mean spindown of over 21 μHz/day, or (-)2.5×10^{-10} Hz/s, significantly more than the mean of 17.7 μHz/day for the previous interval between Feb. 13 and Oct. 31, 1995 (see Fig. 3). However, considering the halt in the increase of the modulation period, this is qualitatively consistent with the pattern seen in the rest of the data (see §4.1), as is the nearly 70 μHz spindown between the weak possible result of Oct. 30th and the stronger result from the 31st, 1995.

The pulse profile of the Feb. 7, '96 data (Fig. B7), generated by incorporating the 288.5 s phase modulation (with a 62° amplitude), was much sharper, particularly when compared to harmonic structure at the fundamental frequency, implying, as in the case of the data for May 16, '93, that the 288.5 s modulation was indeed related to the 2.14 ms pulsation (Table C.3, footnote 't'). This conclusion is strongly supported by both the details of the data and simulations. The contribution to the pulse profile of Fig. B.7 from an unrelated phase modulation with a 62° amplitude and a phase of -93° should have been a sinewave with an amplitude of ~1,000 counts and a maximum at 2.14 ms phase 0.26, or midway through the 5th of the 17 phase bins. The actual rise of the peak at that position, which is at least three times narrower than a sinewave, is two times greater. The large amount of power in the phase modulation spectrum is thus partly a result of the intrinsic sharpness of the pulse being modulated (the first cosine on the right hand side of Eqn. 3 evolves toward a delta function).[23]

In the simulations specifically designed for this event, five peaks of Fourier power were located near the 467.4617 Hz fundamental frequency of data corrected to the solar system barycenter. As described in §B.2.1, phase modulation peaks, with about the same amount of power as occurred for the 288.5 s phase modulation of the 2.14 ms signal (~11 – this criterion severely reduced the number of possible candidates), were identified and incorporated into subsequent folding. Unlike that described in §B.2.1, the folding occurred at the modulated frequency, instead of half of it (and always at the fundamental frequency). Again, although the gain in χ^2 of the demodulated pulse profile was not unusual as compared to simulations, (the chi-square mostly

[23] When the analysis was repeated (over many optimization parameters) with the barycentric correction omitted, in spite of the limited pulse smearing expected from the resulting small component of uncorrected $\frac{\partial f}{\partial t}$ (-1.5×10^{-8} Hz/s at ~467.5 Hz) and the short duration of the pulsations, the significance of the uncorrected result was always lower, consistent with a very sharp pulse of astrophysical origin.

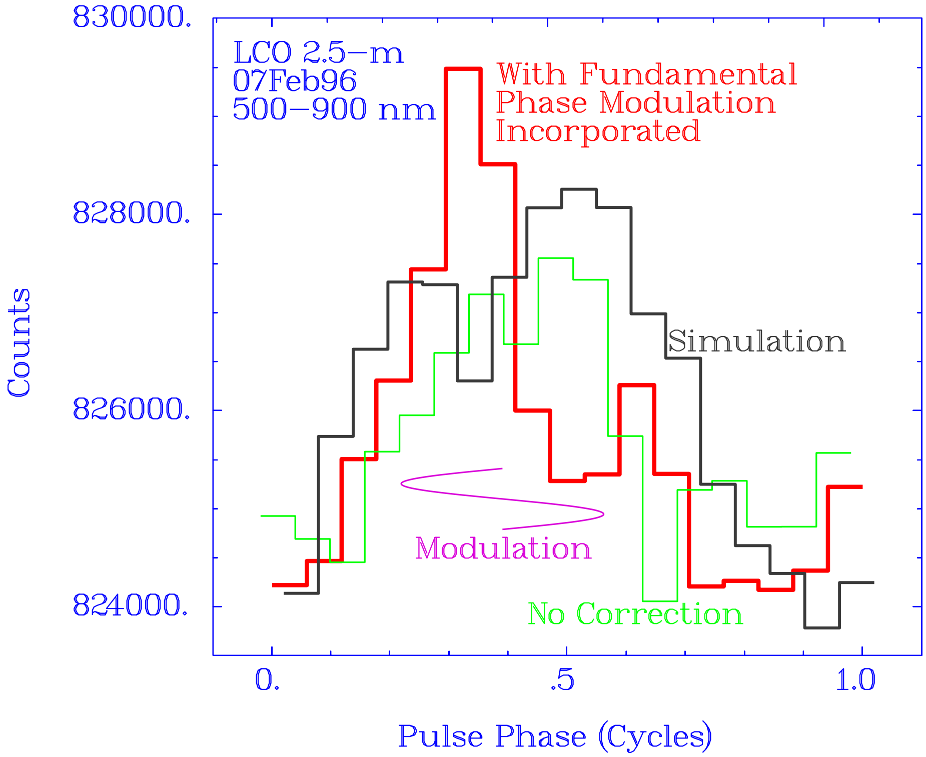

Fig. B.7. The pulse profiles of the 2.14 ms signal found in the data from Feb. 7, '96: (very light profile, displaced toward the right) with no inclusion of the implied 288.5 s phase modulation on the $\sim$ 467.5 Hz fundamental, (darker profile, with a component displaced toward the left) the results of a simulation involving about the same amount of sideband power, and (very dark profile) with the modulation included.

correlates to the total of the original and modulation-incorporated power, and whatever power fortuitously shows up in the higher harmonics), four of the five resulting simulated pulse profiles were very much broader, i.e., essentially sinusoidal, with the fifth profile showing two nearly equal peaks, but with neither of these as sharp as this result at 467.4617 Hz (Fig. B.7).

In addition, the Feb. 7, '96 event is also unusual because the gain of power in the fundamental produced by incorporation of the modulation relative to what was expected, was lower (-2.58) than in any of 53 total simulations, except one, with 8.88 and 15.35 times mean power in the central and modulation peaks respectively (-2.69). Additional tests of "apparent" phase modulation of the actual 467.46173 Hz signal, with periods of 114.5 and 96.1 s, produced unremarkable levels of relative power recovery for the fundamental frequency (-1.08 and -0.69). Although the powers in the FM sidebands for these periods were only half that ($\sim$5) of the 288 s modulation power,[24] making the phase

[24] It is asking too much to get more than one phase modulation peak with power

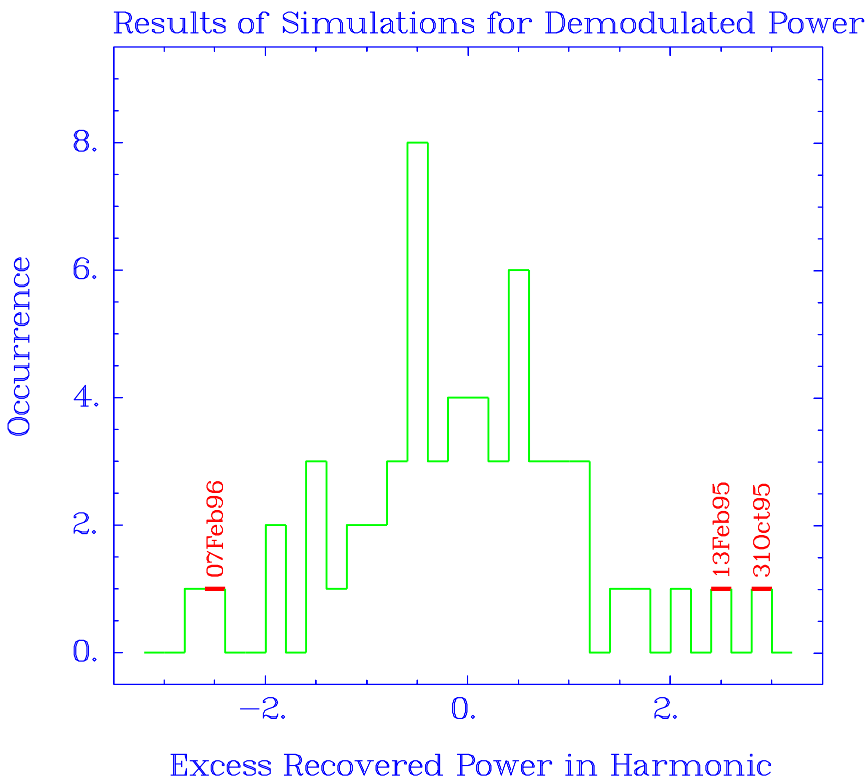

Fig. B.8. The histogram of the occurrence of the relative amounts of power recovered from ~50 simulations.

demodulation power recoveries of these two comparisons susceptible to possible systematic effects, the relative power recoveries of the five power peaks found in other data near the 467.5 Hz fundamental frequency (see above), which all had nearly the full 11 times mean power in the modulation, ranged from -1.82 to +0.34. Thus there is no (large) systematic effect associated *just* with a high ratio of modulation to central power, and therefore the 288.5 s modulation differs in some way from randomly chosen modulations, possibly because of the extreme sharpness of the phase demodulated pulse profile (Fig. B.7).

Figure B.8 plots the results of all of the simulations and includes the results from Feb. 13 and Oct. 31, '95, and Feb. 7, '96. The rms of this distribution without these results is 0.96. The mean of the distribution is -0.115, but without the result from May 16, '93, which is expected to be negative, and the six points obtained from "other" modulation periods near the three "real" 2.14 ms results, five of six of which are negative, it is only -0.027.

near 11 very close to the 2.14 ms fundamental.

C Observations and Tabulated results

We list the observations made of SN1987A from the Chilean observatories which span the interval 1992-1996, in Table C.1. As the moon was near full for the LCO observations, and a considerable color-dependent extinction from Doppler-shifted absorption lines was expected for any possible source (Ph. Pinto, personal communication and Suntzeff et al. (1999), Pinto (1999), Lucy et al. (1991), Bouchet et al. (1991), Dwek (1988), & Suntzeff et al. (1991)), an $\sim$800 nm longpass filter was used with a dry-ice cooled GaAs phototube (with a sensitivity which drops precipitously for wavelengths longer than 900 nm). The typical sensitivity in this filter, with just 53% of the counts achieved in the I filter (equivalent to 1 s^{-1} at $\sim$21.95 magnitudes at the LCO 2.5-m), is barely sufficient to detect the Crab pulsar in 2.5 nights if it were placed at the distance to the LMC, and with half of the $\sim$1 magnitude of (Galactic) extinction in the observation band removed (I$\sim$22) (Middleditch et al. 1987, Kristian 1978, Kristian et al. 1970, Miller 1973, Nandy et al. 1975).

Observations with the U. Tas. 1-m telescope, which commenced after the first year of "detections" at LCO and CTIO, were made with an EMI 9558 photomultiplier tube. Because the signals being seen in the narrow band initially used at LCO and CTIO would have passed undetected by this smaller telescope, no filter was used, but the S20 photocathode restricted the observing band to 320 to 750 nm. The observations made from Tasmania and the HST/HSP are listed in Table C.2.

When it appeared that 2.14 ms pulsations were detected in the more open band used in the Tasmanian search, later runs from LCO and CTIO would employ only a 500 nm longpass filter. V and B filters were used with the TRIFFID micro channelplate system (Shearer et al. 1997, 1998), in addition to a clear filter. A 3.77 arc s circular aperture was used with the LCO runs, while the TRIFFID results employed a 1.25 arc s artificial aperture when possible. The LCO and CTIO data were typically recorded with a 50,000 Hz sampling rate, and summed to 5,000 Hz for ease of analysis. The data from the U. of Tasmania 1-m telescope were originally recorded at 5,000 Hz, and, following the detection on August 23 '93 of very sharp pulse structure, at 10,000 Hz after September of 1993. The HST/HSP data were recorded at 1.024/102 MHz $\sim$ 10,039 Hz. The TRIFFID data had times-of-arrival for the photons to within a fraction of a μs, and so were "clocked" at some convenient frequency for FFT analysis, but could also be folded using the original very fine time resolution in subsequent analyses (Table C.3, footnote 'p').

The upper limits plotted in Fig. 3 and listed in Tables C.3 and C.4 are derived the observed magnitudes listed in these tables and from the 2σ magnitudes listed in Tables C.1 and C.2. An "effective" power level in excess of noise is determined by scaling a power level of 2 (the excess power of a 2σ result, i.e., $e^{-(2+1)}$=0.05) according to the square of the factor equivalent to the difference in the two magnitudes. The level of excess power necessary to exceed the "effective" power only 10% of the time when added to noise is then converted into the magnitude representing the upper limit. For effective power less than 0.35, where the excess power would drop below 1.3 (=ln(10)-1), it is held at 1.3, as such low levels are the result of luck only. For an observation at the 2σ limit, the upper limit magnitude will be 0.47 less, a 54% gain. For an observation with effective power less than 0.35, the upper limit magnitude will be 0.234 higher than the 2 σ level, a 19.4% reduction (or about 1.61σ).

Table C.1
Observations from the Chilean Observatories, 1992-1996

Date	Obs/Tel	Start Time (UT)	End Time (UT)	Total Time (Hrs)	Aper. (arc s)	Band	Sens.[a] (mag.)
14Feb92	LCO2.5m	01:58	06:59	5.02	3.77	≥800nm[b]	22.55
15Feb92	”	01:38	06:25	5.78	”	”	22.56
16Feb92	”	01:18	06:18	5.00[c]	”	”	22.08
06Nov92	”	02:17	08:20	6.06	”	”	22.6
07Nov92	”	01:44	08:48	7.06	”	”	22.2[d]
08Nov92	”	01:09	07:16	5.83	”	”	22.4
03Feb93	”	02:27	08:24	5.95	”	”	21.84
05Feb93	”	02:08	08:29	6.35	”	”	21.84
06Feb93	”	01:11	02:32	1.35	”	”	21.14
07Feb93	”	02:02	07:05	5.05	”	”	21.68
11Feb93	CTIO4m	04:02	09:08	5.10	4.50	”	22.59
12Feb93	”	01:05	07:39	6.57	”	”	22.88
23Nov93	LCO2.5m	02:34	07:04	4.50	3.77	≥500nm[e]	23.97
24Nov93	”	00:39	07:04	6.42	”	”	24.14
27Nov93	”	00:41	07:37	6.93	”	”	24.15
28Nov93	”	00:40	07:13	6.55	”	”	24.04
28Dec93	CTIO4m	01:20	07:50	6.47	3.4	” [f]	24.48
29Dec93	”	01:21	07:52	6.52	”	”	24.39
30Dec93	”	02:49	08:25	5.61	”	”	24.46
20Feb94	LCO2.5m	01:32	05:32	4.00	3.77	” [e]	24.21
21Feb94	”	00:39	06:19	5.67	”	”	24.27
22Feb94	”	00:39	06:50	6.18	”	”	24.27
23Feb94	”	00:45	06:50	6.08	”	≥750nm[g]	22.73
24Feb94	”	01:02	07:06	6.07	”	≥700nm	23.07
25Feb94	”	03:05	05:56	2.85	6.0	J[h]	19.0
26Feb94	”	00:59	05:42	4.71	3.77	≥700nm	21.85

Table C.1
Continued: Observations from the Chilean Observatories, 1992-1996

Date	Obs/Tel	Start Time (UT)	End Time (UT)	Total Time (Hrs)	Aper. (arc s)	Band	Sens.[a] (mag.)
10Nov94	”	01:05	08:06	7.02	”	≥500nm[e]	24.24
11Nov94	”	03:39	08:18	4.64	”	”	24.0
12Nov94	”	01:29	08:23	6.90	”	”	24.22
13Nov94	”	01:43	08:20	6.62	”	”	24.19
14Nov94	”	01:10	08:26	7.27	”	”	24.24
15Nov94	”	01:10	08:11	7.01	”	”	24.17
11Feb95	”	00:47	07:26	6.63	”	”	24.13
12Feb95	”	01:10	08:03	6.88	”	”	24.16
13Feb95	”	01:11	07:16	6.08	”	”	24.11
14Feb95	”	01:18	07:45	6.45	”	”	24.0
15Feb95	”	01:32	05:57	4.42	”	”	23.74
16Feb95	”	01:05	06:40	5.58	”	”	23.88
17Feb95	”	01:06	06:13	5.12	”	”	23.93
23Feb95	NTT	02:42	04:22	1.67	1.25[i]	S20	23.68
24Feb95	”	02:38	05:54	3.27	”	V	23.76
25Feb95	”	02:05	04:37	2.53	”	B	24.2
30Oct95	LCO2.5m	01:55	07:29	5:57	3.77	≥500nm	23.99
31Oct95	”	01:58	08:18	6.33	”	”	24.00
01Nov95	”	01:40	08:29	6.82	”	”	24.09
03Nov95	”	01:41	08:22	6.68	”	”	23.73
03Feb96	”	00:59	07:40	6.68	”	”	23.93
04Feb96	”	00:51	07:44	6.89	”	”	23.89
05Feb96	”	00:47	07:25	6.63	”	”	23.81
06Feb96	”	02:16	07:01	4.74	”	”	23.68
07Feb96	”	00:35[j]	08:21	7.78	”	”	23.95
08Feb96	”	00:32	06:29	5.94	”	”	23.97

Table C.1

Notes on Observations from the Chilean Observatories, 1992-1996 (Continued)

[a]The magnitude of a periodic signal needed to produce a 2 σ result. Infinitely sharp pulses would produce a 4 σ result. The magnitude appropriate for a 7 σ limit, appropriate for sinewaves in the 0-1,000 Hz range of frequencies (higher frequencies suffer more than 6.5% loss, or -0.0724 magnitudes, of snr), not just near 467.5 Hz, can be derived by subtracting 1.36 magnitudes.

[b]The band produced by a Wratten 87 filter and a GaAs photocathode response, roughly 800-900nm.

[c]The weather deteriorated after about 2 hour and 20 min.

[d]The quality of this run was degraded by clouds. Some clouds also affected the following night's run, but fewer.

[e]The band produced by a GG495 filter and a GaAs photocathode response, roughly 500-900 nm.

[f]A gold-coated f/30 secondary for these three runs on the CTIO 4-m set the response at approximately that of a GG495 filter with a GaAs photocathode, still roughly 500-900 nm, but probably more sensitive toward the red end due to the greater reflectivity of gold as opposed to aluminum.

[g]A Wratten 87 filter was used for the first 4 hours and 35 minutes, a Wratten 89B was used for the last hour and a half, (approximately a longpass filter beginning at 700nm). The limit is given for the first part of the run. The Wratten 89B was used for the following two (optical) runs.

[h]This run was made with the Solid State Photomultiplier (SSPM). The instrument had about a 0.5% quantum efficiency in the J band.

[i]This run and the two following were made with a microchannel plate detector with an extended S20 photocathode (TRIFFID). The apertures given were determined by software after the observation. The magnitudes given were determined in the same way as the others. However, the high time resolution (less than 1 μs) allows higher sensitivity to extremely sharp pulse structure. For example the 2σ limit for the 23 Feb. run was near magnitude 25.0 for sharp structure. See Table C.3.

[j] The two σ limit for the first 2^{hr} 18^{min} of this run, prior to and during moonrise, when the seeing was very good and a positive result was obtained (see Table C.3), was 23.19 magnitudes.

Table C.2
Observations from U. Tasmania 1-m[a] & HST/HSP

Date	Start Time (UT)	End Time (UT)	Total Time (Hrs)	Aper. (arc s)	Sens.[b] (mag.) (S20)
16May93	14:43	16:15	1.53	7	21.9
26Jul93	15:02	17:17	2.25	10	21.9
23Aug93	15:39	18:08	2.07[c]	10	22.0
24Aug93	12:34	17:50	4.17	10	22.1
27Aug93	16:52	19:37	2.62	10	21.8
12Sep93	12:57	19:02	5.33	10	22.4
13Sep93	16:06	17:35	1.49	10	21.6
24Sep93	16:43	18:43	2.00	10	21.9
08Oct93	12:49	18:32	3.46	10	22.1
13Oct93	16:43	18:43	2.48	10	22.0
12Nov93	12:45	17:15	4.50	10	22.3
15Nov93	12:28	17:10	4.70	10	22.5
09Dec93	13:45	16:45	3.00	10	22.0
10Dec93	12:28	15:20	3.31	10	22.0
20Jan93	14:57	17:21	2.41	10	22.0
03Feb94	12:23	14:35	2.20	10	21.9
09Feb94	13:25	17:22	3.97	10	22.1
12Feb94	13:07	14:17	1.17	10	21.9
13Feb94	13:34	16:49	3.25	10	22.4
07Mar94	11:54	15:46	3.87	10	22.6
04May94	16:13	17:24	1.18	10	21.4
03Aug94	16:43	19:30	2.78	10	22.1
11Oct94	16:40	18:50	1.83	7	22.2
09Jan95	14:32	17:15	2.72	7	22.8
24Feb95	14:46	17:57	3.18	10	21.9

Table C.2
Continued: Observations from HST/HSP[d] & Notes

Date	Start Time (UT)	End Time (UT)	Total Time (Hrs)	Aper. (arc s)	Sens.[b] (mag.) (S20)
02Jun92	11:03	11:43	0.66	0.6	23.38
22Nov92	19:23	20:03	0.66	0.6	23.48
06Mar93	21:46	22:06	0.33	0.6	22.82
06Mar93	23:13	23:33	0.33	0.6	22.82
04Nov93	15:42	16:16	0.57	0.6	23.45

[a]All observations were made with an unfiltered EMI 9558 photomultiplier tube.
[b]The magnitude of a periodic signal needed to produce a 2 σ result. Infinitely sharp pulses would produce a 4 σ result.
[c]This data consists of two ~1-hour observations separated by a 1/2-hour gap. The first hour's observations was discontinued due to bad seeing and impending clouds.
[d]These observations were made with a 160 nm long pass filter, a 0.6 arc s aperture, and an S20 photocathode response, which drops after 750 nm.

Table C.3
Results for the Chilean Observatories, 1992-1996

Date (UT)	Frequency[a] (Hz)	Harmonic Content	Magn.[b]	Prob.[c]	Detection Yes/No/?	Upper Limit
14Feb92	467.4934033(74) [d]	3+1	21.78(0.3)	0.0021	Yes	
15Feb92	467.4933838(32)	1+2	21.73(0.2)	4.6×10^{-6}	Yes	
16Feb92	467.4933735(64)	2+1	21.43(0.2)	2.3×10^{-5}	Yes	
06Nov92	467.4875389(20)	2+3	21.69(0.2)	$3.\times10^{-4}$	Yes[e]	
07Nov92	467.4875226(200)		24.7(1.0)	0.69	No	22.43
08Nov92	467.4875063(25)	2+3	22.00(0.25)	0.017	?	
03Feb93	467.4842934(42)	1+2	22.34(0.25)	0.046	?	
05Feb93	467.4843157(83)	2	21.86(0.25)	0.15	?[f]	21.41
06Feb93	467.4842946(75)	1+2	20.87(0.2)	$1.\times10^{-4}$	Yes	
07Feb93	467.4842587(25)	2+1	21.56(0.2)	0.011	?[g]	
11Feb93	467.4842990(41)	2+1	22.57(0.2)	0.0011	Yes	
12Feb93	467.4843012(22)	3+2	22.72(0.2)	0.038	Yes	
23Nov93	467.4773350(75)	2+1	23.23(0.2)	0.004	?[h]	
24Nov93	467.4773499(75)		24.12(0.3)	0.11	No	23.66
27Nov93	467.4773001(37)	1+3+2	23.23(0.2)	0.002	Yes[i]	
28Nov93	467.4773388(30)		23.98(0.3)	0.096	No	23.53
28Dec93	467.4766273(30)	2+3	24.77(0.2)	0.044	Yes[j]	
29Dec93	467.4766060(75)	2	24.44(0.3)	0.14	Yes[j]	24.01
30Dec93	467.4765791(37)	3+1	24.78(0.2)	7.5×10^{-4}	Yes	
20Feb94	467.4754776(22)	2+3	23.3(0.2)	0.0074	?	23.07
21Feb94	467.4754333(37)		24.57(0.3)	0.34	No[k]	24.01
22Feb94	467.4754242(45)	1+2	23.26(0.2)	0.0021	?[l]	
23Feb94	467.4755545(50)		23.33(0.3)	0.57	No	22.69
24Feb94	467.4754034(50)		23.28(0.3)	0.19	No	22.75
25Feb94	467.4754097(50)		20.5(0.3)	0.83	No	19.23
26Feb94	467.4753555(80)		22.35(0.3)	0.47	No	21.73

Table C.3
Continued: Results for the Chilean Observatories, 1992-1996

Date (UT)	Frequency[a] (Hz)	Harmonic Content	Magn.[b]	Prob.[c]	Detection Yes/No/?	Upper Limit
10Nov94	467.4702579(20)	2+3	23.52(0.3)	6.8×10^{-5}	Yes	
11Nov94	467.4702838(35)	2	24.07(0.3)	0.0061	Yes[m]	
12Nov94	467.4702719(25)	2+1	24.26(0.3)	0.0022	Yes[m]	
13Nov94	467.4702611(35)		24.6(0.3)	0.18	No	24.01
14Nov94	467.4702566(30)		24.3(0.3)	0.37	No	23.83
15Nov94	467.4701821(30)	2	24.8(0.5)	0.021	No[n]	24.26
11Feb95	467.4684705(30)	2	24.0(0.3)	0.019	No	23.57
12Feb95	467.4684660(30)	1+2	25.0(0.3)	0.25	No	24.31
13Feb95	467.4684442(20)	2	23.73(0.3)	4.6×10^{-5}	Yes[o]	
14Feb95	467.4684226(30)	2	24.54(0.3)	0.57	No	23.91
15Feb95	467.4683965(35)		24.0(0.3)	0.39	No	23.46
16Feb95	467.4683891(35)		24.84(0.3)	0.40	No	24.11
17Feb95	467.4683660(30)	3	24.02(0.3)	0.042	No	23.53
23Feb95	467.4681961(30)	2+3	23.7(0.3)	5.5×10^{-5}	Yes[p]	
24Feb95	467.4682679(30)	2	23.66(0.3)	0.37[q]	No	22.91
25Feb95	467.4681356(30)		23.95(0.3)	0.19[q]	No	23.55
30Oct95	467.4639121(25)	2+3	24.09(0.3)	0.07	?[r]	23.57
31Oct95	467.4638454(20)	2+3[s]	23.98(0.3)	0.0065	Yes[s]	
01Nov95	467.4638405(20)		24.70(0.3)	0.21	No	24.00
03Nov95	467.4637899(35)		24.92(0.4)	0.54	No	23.96
03Feb96	467.4618393(20)	3	23.60(0.3)	0.056	No	23.22
04Feb96	467.4618095(20)		23.26(0.4)	0.09	No	22.96
05Feb96	467.4618266(20)	2+4	23.58(0.2)	0.025	No	23.18
06Feb96	467.4617708(30)		23.55(0.3)	0.13	No	23.12
07Feb96	467.4617295(30)	1+2	23.0(0.2)	4.7×10^{-4}	Yes[t]	
08Feb96	467.4616851(30)		23.69(0.3)	0.02	?	23.30

Table C.3
Continued: Results for the Chilean Observatories, 1992-1996

[a]Unless otherwise noted, this is the frequency of the locally highest χ^2 from folding the 2.14 ms signal which is nearest to the extrapolated frequency into 20 bins (17 for the later runs).
[b]The observing bands for these magnitudes are listed in Table C.1.
[c]The probability is derived solely from the χ^2 of the pulse profile binned into 11ths of the pulse cycle at the optimum frequency determined from folding into 20 or 17 bins, as described in the text and notes to Table 1.
[d]The mean frequency derived from only the first two harmonics (near 467.5 and 935 Hz) is 467.4933921(74) Hz, closer to the backward extrapolation of the individual frequencies from the following two nights. The probability at this frequency is 0.019. The frequency in this table results from a strong third harmonic contribution, which could be partly noise.
[e]The signal consists of 2nd and 3rd harmonics, plus a second upper sidelobe (+ 2/1,100 Hz) of the fundamental frequency. Both of these show 1,100 s phase modulation (see Appendix B, §B.1). This was the best night of the three in Nov. '92.
[f]This signal consists mainly of a second harmonic and an upper (+ 1/935 Hz) sidelobe to the fundamental, yet the frequency and pulse profile seem acceptable.
[g]Both this run and that of 3 Feb. '93 become more significant when only the last half of the runs are analyzed. However, the frequencies of both are reduced, typically by about 40 μHz, and the pulse profiles appear less sharp when this is done, possibly indicating that this effect is due to noise (the 2nd halves of these runs were subject to slightly worse observing conditions). If so, then the actual frequencies of both might be higher by about 20 μHz.
[h]This result is from the 2nd half of the run, which had a lower airmass and superior observing conditions.
[i]A broad complex of power was observed in the sum spectrum for the whole run near this frequency, which only became clear in the sum spectra for the 2nd half. Phase modulation with a period near 1,035 s was present in several harmonics. When the time-like part of this modulation was included, the probability of the result dropped to 1.54×10^{-6}.
[j]This result and those of the next two nights are consistent with a mean frequency of 467.476604 Hz, very close the mean frequency derived from the three individual nights, and a spindown of 2.5×10^{-10} Hz/s, consistent with the decline of the individual frequencies very close the slope extrapolated from previous data. The pulse profile has a probability of 1.5×10^{-4}. The second harmonic is present mostly in the first two nights of data, while the third harmonic is present in the last two nights of data, yet the implied frequencies and time derivatives, obtained from a Fourier transform of all three nights of data, occur in perfect harmonic ratios.
[k]This result is derived from the 2nd half of this run. The whole run showed less.

Table C.3
Continued: Results for the Chilean Observatories, 1992-1996

[l]This result appears weakly in the whole run but is stronger during the middle half.
[m]Because of the proximity of the frequencies, the validity of these two results is tied to that of 10 Nov. '94.
[n]A less significant signal was also found at 467.4702188 Hz with a magnitude of 23.99 and probability of 0.19. However, the signal listed in the table had a dominant 2nd harmonic, similar to the results from 10-12 Nov., and could be real if the decline in frequency since 12 Nov. was closer to the more typical 21 μHz/day.
[o]When this run was compensated for the 4th harmonic of the implied 1,120 s modulation (280 s) of the 2.14 ms 2nd harmonic (Table C.5), the power in this harmonic increased from 10.5 to 21 times mean, far more than expected (+2.98 in excess – see §B.3.1). Thus, in spite of the fact that the pulse profile did not substantially sharpen as in §§B.2.1 and B.3.2, it is very likely that the 1,120 s modulation is actually associated with the 2.14 ms signal.
[p]This detection and its stated probability resulted from sharp structure in the data when folded into 11 independent bins. A check of some 10,000 other pulse profiles showed this was the most significant such result for at least $\pm$ 1 mHz around the quoted frequency. When this data was "clocked" at 5,000 Hz and folded into 11 bins, as done for the rest of the data, the associated probability was 0.00107.
[q]The probabilities for these results were 0.025 and 0.032 when the data were folded into 11 bins using the full time resolution. This difference is probably numerical only, i.e., the higher resolution data will always produce lower probabilities by about an order of magnitude (see footnote 'p' just above).
[r]This result is a possible detection due to the proximity to the frequency on the following night. These first two nights were the best of this series of four.
[s]Although this result was discovered with the help of a sharp third harmonic Fourier power peak, the actual signal, which shows both first and *second* order phase modulation power with a period of 582 s, very close to the 2nd harmonic of the nominal 1,164 s modulation (see §B.3.1 and Table C.5), was mostly 2nd harmonic. There is almost no contribution left from the third harmonic due to the extreme ($1.5 \times 95.^\circ5$) phase modulation at that frequency. The excess gain in power from incorporating the modulation, +3.95, is the highest of 47 simulations and the handful of candidate 2.14 ms signals analyzed, and the power with the appropriate phase in the 2nd order phase modulation (which appears in the AM spectrum – see §3.1) is a very rare occurrence (see §B.3.1 and Table C.5, footnote 'k').
[t]This result is from the first 2^{hr} 18^{min} of the run prior to and during moonrise. The seeing was excellent for this first section, and deteriorated after it. Strong phase modulation of the fundamental at the 4th harmonic of 1154 s (see Table C.5) *sharpens* the main pulse dramatically (from duty cycle $\sim$0.5 to $\sim$0.15) when incorporated in the folding, giving a pulse profile with a probability of 1.25×10^{-10} (see Fig. B.7 and §B.3.2).

Table C.4
Results from U. of Tasmania 1-m and HST/HSP

Date (UT)	Frequency[a] (Hz)	Harmonic Content	Magn.[b]	Prob.[c]	Detection Yes/No/?	Upper Limit
16May93	467.482018(50)	2+3	21.6	1.6×10^{-4}	Yes[d]	
26Jul93	467.480564(10)	1+2	21.6	2.7×10^{-7}	Yes	
23Aug93	467.479873(12)		21.6	0.35	No[e]	
23Aug93	467.479886(4)	1-5	20.72	2.1×10^{-4}	Yes[e]	
24Aug93	467.479850(3)	3	22.3	0.54	No	21.78
27Aug93	467.479855(4)	3+2	21.5	0.064	No[f]	21.11
12Sep93	467.479353(6)	2+4	21.6	2.6×10^{-3}	?[g]	
13Sep93	467.479373(12)		21.9	0.14	No	21.34
24Sep93	467.479142(13)	1+2	22.1	0.027	?[h]	21.57
08Oct93	467.478649(5)	2+1	22.3	0.076	No[i]	21.78
13Oct93	467.478420(5)	1+2	21.65	0.003	?[j]	21.28
12Nov93	467.477826(5)	1	22.57	0.095	No	22.01
15Nov93	467.477495(5)	2+3	21.24	0.05	?[k,l]	21.05
09Dec93	467.477165(5)	1+2	21.52	0.012	?[l]	21.18
10Dec93	467.476970(5)		22.9	0.15	No	22.17
20Jan94	467.475970(5)	1+2	21.72	0.0023	?[l,m]	21.33
03Feb94	467.475817(7)		23.56	0.77	No	22.13
09Feb94	467.475762(5)		22.17	0.16	No	21.68
12Feb94	467.476066(5)		21.74	0.13	No	21.32
13Feb94	467.475785(5)	1+2	22.43	0.007	No	21.91
07Mar94	467.475113(5)		22.79	0.14	No	22.53
04May94	467.473944(5)	2	21.39	0.08	No	20.93
03Aug94	467.472186(5)	1+3	22.13	0.0015	?	21.65
11Oct94	467.470967(7)	3	22.17	0.018	No	21.71
09Jan95	467.468914(5)	1+2+3	23.09	0.0066	?	22.74
24Feb95	467.468258(7)	5+2	21.71	0.007	No	21.30

Table C.4
Continued: Results from U. of Tasmania and HST/HSP

Date (UT)	Frequency[a] (Hz)	Harmonic Content	Magn.[b]	Prob.[c]	Detection Yes/No/?	Upper Limit
02Jun92	467.492310(7)	3+2	22.70	0.0011	Yes	
22Nov92	467.487135(10)	1+5	23.00	0.010	No	22.66
06Mar93	467.484065(7)	3+2+1	22.33	0.0014	Yes	
06Mar93	467.484032(10)	3+5	22.91	0.22	Yes[n]	22.42
04Nov93	467.477911(10)	2+3+4	23.17	0.04	No	22.78

[a]See footnote 'a' to Table C.3.
[b]The observing band for this magnitude is that of an S20 photocathode, or ~320-750 nm (in the case of the HST/HSP, 160-750 nm).
[c]The probability is derived solely from the chi-square of the pulse profile, as 5,000 Hz data are folded into 11 bins (See footnote 'c' to Table C.3).
[d]The probability for the 11-bin pulse profile, without the phase modulation incorporated, is 0.016 (see Fig. B.1 and §B.2.1).
[e]The run on Aug. 23, '93 consists of two hour-long data segments separated by a one half hour gap. See §B.2.2 for details.
[f]If this peak on 27Aug93 *is* due to the pulsar, then the pulse frequency dropped by only 19 μHz in four days. It's (apparent) negative frequency derivative agrees with that expected due to rotation of the Earth during the run.
[g]This signal from 12Sep93 is present only in the first 2.3 hours of 5.3 observed and shows a $\frac{\partial f}{\partial t}$ of -3.45$\times 10^{-8}$ Hz/s. See §B.2.3 for details.
[h] The UT Sep. 24 result listed in Table C.2 has 2, 2-σ harmonics with the appropriate relation between frequency and phase, and this, together with the approximate knowledge of the pulse frequency and the similarity between its pulse profile and those previously obtained (see Fig. B.3), make it a very probable detection.
[i]This run from 8Oct93, and the other on 13 Oct., were affected by possible timing problems in recording the data.
[j]A 2-hour gap in the 13Oct93 data also allows 467.478342 and 467.478548 Hz solutions, though both with probabilities near 0.07. Again, timing problems could be affecting the results.
[k]The result from 15Nov93 was stronger in the last 2/3rds of the data, with a probability ten times lower at 0.0054.

Table C.4
Continued: Results form U. of Tasmania and HST/HSP

[l]These results (15Nov93, 9Dec93, and 20Jan94) are probably not real as they are too bright wrt the candidates obtained close to this date from the larger telescopes.
[m]The low probability of the 20Jan94 pulse profile results from a sharp dip, rather than a strong pulse.
[n]This weak result is consistent with the positive result obtained one HST orbit earlier, and the result from the combined data from the two orbits is consistent with these frequencies and slightly more significant than the result from the first orbit.

Table C.5
Pulsar modulation parameters for 1992-1996

Date 1[a] (UT)	Date 2[b] (UT)	Mean[c] Period (s)	Mod.[d] Type	Harmonic[e] (2.14 ms)	Harmonic[f] (~1,000 s)
14Feb92	15Feb92	1430.0(3.0)	AM	2nd	1st
14Feb92	15Feb92	1429.2(1.0)	AM	2nd	3rd
15Feb92	16Feb92	1431.1(3.0)[g]	FM	1st	1st
15Feb92	16Feb92	1429.8(1.0)[g]	FM	1st	3rd
06Nov92	08Nov92	1099.9(2.0)	FM	2nd	1st
06Nov92	08Nov92	1100.5(0.8)	FM	2nd	3rd
06Nov92	08Nov92	1100.7(1.2)	FM	2nd	2nd
03Feb93	06Feb93	938.9(0.5)	AM	2nd	1st
03Feb93	06Feb93	938.8(0.2)	AM	2nd	2nd
03Feb93	06Feb93	938.9(0.2)	FM	1st	2nd
05Feb93	06Feb93	936.9(1.5)	AM	1st	1st
05Feb93	06Feb93	937.6(0.8)	AM	1st	2nd
05Feb93	06Feb93	936.2(1.5)	FM	2nd	1st
06Feb93	06Feb93	935.2(1.7)	SB±	1st,2nd	8-10,12[h]
06Feb93	07Feb93	935.0(0.8)	FM	1st	2nd
06Feb93	07Feb93	932.0(1.5)	AM	2nd	1st
06Feb93	07Feb93	934.4(0.8)	AM	2nd	2nd
06Feb93	11Feb93	929.6(0.3)	FM	1st	1st
06Feb93	11Feb93	929.6(0.2)	AM	1st	2nd
11Feb93	12Feb93	922.7(1.5)	FM	1st	1st
11Feb93	12Feb93	922.5(0.8)	AM	2nd	2nd
16May93	16May93	1008.4(17.)	FM	2nd	1st
26Jul93	26Jul93	1005.(30.)	SB+	1st	1st
26Jul93	26Jul93	990.7(7.4)	AM	1st	2nd
26Jul93	26Jul93	999.(10.4)	FM	1st	3rd
26Jul93	26Jul93	997.(8.)	SB+	1st	4th

Table C.5
Continued: Pulsar modulation parameters for 1992-1996

Date 1[a] (UT)	Date 2[b] (UT)	Mean[c] Period (s)	Mod.[d] Type	Harmonic[e] (2.14 ms)	Harmonic[f] (~1,000 s)
27Nov93	27Nov93	1035.(10.0)	SB±	1-4	1-2[i]
10Nov94	10Nov94	1102.(14.)	SB+	1st	1st[j]
10Nov94	10Nov94	1102.(10.)	AM	1st	3rd
10Nov94	10Nov94	1102.(4.)	FM	3rd	2nd
10Nov94	10Nov94	1102.(10)	FM	3rd	1st[j]
11Nov94	11Nov94	1120.(15.)	AM	3rd	1st
13Feb95	13Feb95	1127.(15.)	SB+	3rd	1st
13Feb95	13Feb95	1122.(3.)	FM	3rd	4th
13Feb95	13Feb95	1121.(3)	FM	2nd	4th
31Oct95	31Oct95	1164.(5.)	FM	2nd	2nd[k]
31Oct95	31Oct95	1164.(3.)	AM	2nd	4th[k]
07Feb96	07Feb96	1154.(4.6)	FM	1st	4th

[a]This is the first date on which the modulation period was timed.
[b]This is the second date on which the modulation period was timed. When these are the same the modulation was timed only during one night's observation.
[c]This is the mean modulation period for the interval over which the modulation was phased.
[d]As explained in §3.1, there are two types of modulation which produce symmetric sidebands, AM, and FM. There is also the possibility of a single peak (SB±) with frequency higher (+) or lower (-) than the given harmonic of the established 2.14 ms frequency, which has no counterpart on the opposite side. The errors in the modulation frequency for an FM or AM sidelobe are generally smaller than those for an SB peak, since the latter adds two errors in quadrature (those of the central peak and the SB).
[e]This is the harmonic of the 2.14 ms signature for which the modulation or solitary sideband was observed. (Harmonic number N = N$\times$ ~467.5 Hz).
[f]This is the harmonic of the ~1,000 s period which was observed to modulate (or to occur near to) the stated harmonic of the 2.14 ms signal.
[g]When these data are folded with the 1st and 3rd harmonics of the ~1430 s modulation incorporated, the period is much more accurately determined to be 1428.5(0.2) s.

Table C.5
Continued: Pulsar modulation parameters for 1992-1996

[h]The modulation period was determined by the locations of the 8th, 9th, 10th, and 12th sidebands to the fundamental and 2nd harmonic of the 2.14 ms period.
[i]The modulation was visible as first sidelobes in the FM spectrum for the 1st, 2nd, and 4th harmonics, and as a second sidelobe in the AM spectrum (thus possibly a second order FM sideband) for the 3rd harmonic of the 2.14 ms period.
[j] The FM peak is nearly as significant as this upper sideband and gives 1109 ± 7 s for the estimated period. Both the 2nd and third harmonics of this signal produce extensive nearby sidebands in their respective FM modulation spectra and none in their AM spectra. The fundamental FM peak on the 2.14 ms third harmonic is less significant, with only 2.8 times mean power.
[k]These modulation harmonics are phased in such a way as to indicate that they are 1st and 2nd order phase modulation consistent with a 95.5° modulation of the time of arrival of the 2.14 ms signal with a period of 582 s (see §3.1, Eqn. 4, and Appendix B, §B.3.1).

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